

FORM PTO-1390 (REV. 9-2001)		U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE		ATTORNEY'S DOCKET NUMBER 14836-1US JA/AD	
TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371				U.S. APPLICATION NO. (If known, see 37 CFR 1.5) 10/069876	
INTERNATIONAL APPLICATION NO. PCT/CA00/01026		INTERNATIONAL FILING DATE September 1, 2000		PRIORITY DATE CLAIMED September 3, 1999	
TITLE OF INVENTION SEVERAL GAS FLOW MEASURING DEVICES AND SIGNAL PROCESSING METHODS					
APPLICANT(S) FOR DO/EO/US					
Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:					
1. <input checked="" type="checkbox"/> This is a FIRST submission of items concerning a filing under 35 U.S.C. 371. 2. <input type="checkbox"/> This is a SECOND or SUBSEQUENT submission of items concerning a filing under 35 U.S.C. 371. 3. <input checked="" type="checkbox"/> This is an express request to begin national examination procedures (35 U.S.C. 371(f)). The submission must include items (5), (6), (9) and (21) indicated below. 4. <input checked="" type="checkbox"/> The US has been elected by the expiration of 19 months from the priority date (Article 31). 5. <input checked="" type="checkbox"/> A copy of the International Application as filed (35 U.S.C. 371(c)(2)) a. <input checked="" type="checkbox"/> is attached hereto (required only if not communicated by the International Bureau). b. <input type="checkbox"/> has been communicated by the International Bureau. c. <input type="checkbox"/> is not required, as the application was filed in the United States Receiving Office (RO/US). 6. <input type="checkbox"/> An English language translation of the International Application as filed (35 U.S.C. 371(c)(2)). a. <input type="checkbox"/> is attached hereto. b. <input type="checkbox"/> has been previously submitted under 35 U.S.C. 154(d)(4). 7. <input checked="" type="checkbox"/> Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371(c)(3)) a. <input type="checkbox"/> are attached hereto (required only if not communicated by the International Bureau). b. <input type="checkbox"/> have been communicated by the International Bureau. c. <input checked="" type="checkbox"/> have not been made; however, the time limit for making such amendments has NOT expired. d. <input type="checkbox"/> have not been made and will not be made. 8. <input type="checkbox"/> An English language translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371 (c)(3)). 9. <input checked="" type="checkbox"/> An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)). 10. <input type="checkbox"/> An English language translation of the annexes of the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)). Items 11 to 20 below concern document(s) or information included: 11. <input type="checkbox"/> An Information Disclosure Statement under 37 CFR 1.97 and 1.98. 12. <input type="checkbox"/> An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included. 13. <input checked="" type="checkbox"/> A FIRST preliminary amendment. 14. <input type="checkbox"/> A SECOND or SUBSEQUENT preliminary amendment. 15. <input type="checkbox"/> A substitute specification. 16. <input type="checkbox"/> A change of power of attorney and/or address letter. 17. <input type="checkbox"/> A computer-readable form of the sequence listing in accordance with PCT Rule 13ter.2 and 35 U.S.C. 1.821 - 1.825. 18. <input type="checkbox"/> A second copy of the published international application under 35 U.S.C. 154(d)(4). 19. <input type="checkbox"/> A second copy of the English language translation of the international application under 35 U.S.C. 154(d)(4). 20. <input checked="" type="checkbox"/> Other items or information: Form PCT/IB/306; Form PCT/ISA/220; Form PCT/ISA/210; copy of our letter to EPO International Searching Authority with new Abstract; Form PCT/IB/308; Form PCT/ISA/206; Form PCT/IPEA/402; Form PCT/IB/332.					

U.S. APPLICATION NO. 10/069876		INTERNATIONAL APPLICATION NO. PCT/CA00/01026		ATTORNEY'S DOCKET NUMBER 14836-IUS JA/AD	
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21. <input checked="" type="checkbox"/> The following fees are submitted: BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)): Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO \$1040.00 International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO \$890.00 International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO \$740.00 International preliminary examination fee (37 CFR 1.482) paid to USPTO but all claims did not satisfy provisions of PCT Article 33(1)-(4) \$710.00 International preliminary examination fee (37 CFR 1.482) paid to USPTO and all claims satisfied provisions of PCT Article 33(1)-(4) \$100.00 ENTER APPROPRIATE BASIC FEE AMOUNT =				CALCULATIONS PTO USE ONLY	
				\$ 890.00	
Surcharge of \$130.00 for furnishing the oath or declaration later than <input type="checkbox"/> 20 <input type="checkbox"/> 30 months from the earliest claimed priority date (37 CFR 1.492(e)).				\$	
CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE	\$	
Total claims	14 - 20 =		x \$18.00	\$	
Independent claims	2 - 3 =		x \$84.00	\$	
MULTIPLE DEPENDENT CLAIM(S) (if applicable)			+ \$280.00	\$	
TOTAL OF ABOVE CALCULATIONS =				\$ 890.00	
<input checked="" type="checkbox"/> Applicant claims small entity status. See 37 CFR 1.27. The fees indicated above are reduced by 1/2.				\$ -445.00	
SUBTOTAL =				\$ 445.00	
Processing fee of \$130.00 for furnishing the English translation later than <input type="checkbox"/> 20 <input type="checkbox"/> 30 months from the earliest claimed priority date (37 CFR 1.492(f)).				\$	
TOTAL NATIONAL FEE =				\$ 445.00	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). \$40.00 per property +				\$	
TOTAL FEES ENCLOSED =				\$ 445.00	
				Amount to be refunded:	\$
				charged:	\$

a. ☒ A check in the amount of \$ 445.00 to cover the above fees is enclosed.

b. ☐ Please charge my Deposit Account No. _____ in the amount of \$ _____ to cover the above fees.
 A duplicate copy of this sheet is enclosed.

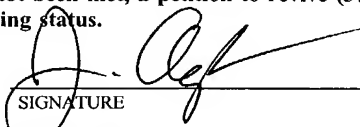
c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any
 overpayment to Deposit Account No. 19-5113. A duplicate copy of this sheet is enclosed.

d. ☐ Fees are to be charged to a credit card. **WARNING:** Information on this form may become public. **Credit card
 information should not be included on this form.** Provide credit card information and authorization on PTO-2038.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR
 1.137 (a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO:

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 SIGNATURE
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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicants: Oleg GRUDIN et al.
Serial No.: unknown (national stage of PCT/CA00/01026)
International Filing date: September 1, 2000
35USC§371 date: herewith
Title: SEVERAL GAS FLOW MEASURING DEVICES AND
SIGNAL PROCESSING METHODS
Attorney or agent of Record: James Anglehart Tel.: (514) 847-4244
Attorney docket: 14836-1US JA/AD/ld

ASSISTANT COMMISSIONER FOR PATENTS,
Washington, D.C. 20231,
U.S.A.

PRELIMINARY AMENDMENT

Sir:

Prior to calculating the fees due in this national stage application,
please amend the above-identified application as follows:

IN THE CLAIMS:

Please cancel claims 15 to 32 presently on file without prejudice.
Please amend claims 8-10 and 13-14 as follows.

8. (amended)The apparatus as claimed in claim 1, wherein said elements are
sensitive to vibration or acceleration along only one axis.

9. (amended)The apparatus as claimed in claim 1, wherein said apparatus comprises
two of said elements.

Ser. No. 09/*

- 2 -

10. (amended) The apparatus as claimed in claim 1, wherein said elements comprise thermoanemometer-type transducers.

13. (amended) The gas flow receiver as claimed in claim 11, wherein said diaphragm is shaped so as to exhibit high drag and generate maximum accentuated pressure for its size.

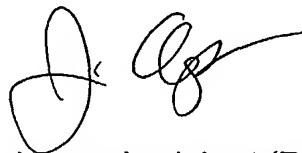
14. (amended) The gas flow receiver as claimed in claim 11, wherein said flow tube has a smaller cross-section between said orifices and is similarly tapered on both sides of said small cross-section.

- R E M A R K S -

The claims have been amended to reduce the claim fees payable at this time.

Respectfully submitted,
Oleg GRUDIN et al.

By:



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Ser. No. 09/*

- 3 -

Marked-up Copy of Amendments to Claims

8. (amended) The apparatus as claimed in ~~any one of claims 1 to 4, 6 and 7,~~ wherein said elements are sensitive to vibration or acceleration along only one axis.

9. (amended) The apparatus as claimed in ~~any one of claims 1 to 4, and 6 to 8,~~ wherein said apparatus comprises two of said elements.

10. (amended) The apparatus as claimed in ~~one of claims 1 to 9,~~ wherein said elements comprise thermoanemometer-type transducers.

13. (amended) The gas flow receiver as claimed in claim ~~11 or 12,~~ wherein said diaphragm is shaped so as to exhibit high drag and generate maximum accentuated pressure for its size.

14. (amended) The gas flow receiver as claimed in claim ~~11, 12 or 13,~~ wherein said flow tube has a smaller cross-section between said orifices and is similarly tapered on both sides of said small cross-section.

ABSTRACT

A gas flow receiver has a non-symmetrical-flow-inducing diaphragm mounted in a flow tube causing accentuated higher pressure near an upstream orifice than would be sensed in a corresponding cross-section of the flow tube and accentuated lower pressure near a downstream orifice. A gas flowmeter using thermoanemometer-type transducers receiving gas flow from the upstream orifice is made immune to vibration or acceleration, for example, by arranging a pair of transducers parallel to one another with the gas flow passing serially through them, but in opposite directions. Signal filtering is provided by varying the sample-averaging period as a function of the transducer's analog signal amplitude, such that the sample-averaging period is longer for lower amplitude values and shorter for higher amplitude values. Since the flowmeter has a non-linear response, a calibrated output signal representing flow is obtained by forming an analytical solution for the non-linear function, by polynomial fitting, using sub-linear powers.

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**GAS FLOW MEASURING APPARATUS AND SIGNAL PROCESSING
METHODS APPLICABLE THERETO**

Field of the Invention

5 The present invention relates generally to gas flowmeters containing one or more differential pressure transducers measuring pressure drop across a flow-resistive element placed inside the gas passageway. More particularly, the present invention relates to improvement in the accuracy of flowmeters used in spirometry, by special design of the gas passageway, 10 by increasing its immunity to vibrations and by providing special signal processing and a linearization method applicable to a flowmeter or other like transducer signals.

Background

15 Typically, a gas flowmeter contains a gas flow receiver (GFR) (also called gas passageway), a tube through which gas flow passes, and a differential pressure transducer thus connected to the GFR. The transducer measures differential pressure generated by a flow-resistive element placed inside the tube. For certain applications, such as spirometry, GFRs 20 having simple shape, providing easy cleaning and/or disposability, are the most attractive. Among GFRs used in industry and medicine, one can find tubes with flow-resistive elements made in the form of plane diaphragms (flow-obstacles designed to create local differential pressure while allowing flow). The closest prototype used in spirometry, is the GFR with crest-like 25 flow-resistive element [US Patent 5038773].

 The particular design of the GFR used in spirometry is the result of a trade-off between the imperative to increase differential pressure generated by the flow-resistive element to obtain higher sensitivity of the flowmeter, and the requirement not to exceed a maximum acceptable back-pressure 30 specified by spirometry standards. For example, the American Thoracic Society Standards for Spirometry (1994) require the back-pressure to be

not greater than 150 Pa·s/l in the whole operating range. Therefore a GFR with highest ratio (differential pressure)/(back pressure) is preferable for this particular application.

Another problem to be solved in the described flowmeter is related to reproducibility of the transformation characteristic of the GFR, which defines flow-to-differential-pressure conversion. For this purpose, simpler shapes of the GFR are easier to manufacture, with better reproducibility of the dimensions of the inner features and surface of the tube, which eventually guarantee reproducibility of the conversion. Another result of the tube shape simplification is the reduction of manufacturing costs, which is of great importance, especially for disposable tubes.

It has been shown [US Patent 5038773] that GFRs with flow-resistive elements made in the form of plane diaphragms have essentially non-linear flow-to-differential-pressure conversion characteristics. Typically, the differential pressure which is generated by this type of GFR is close to a square function of the flow, which results in the following problem. A requirement to measure flow in a dynamic range of 10^3 , say from 15ml/s to 15l/s (spirometry), necessitates the measurement of differential pressure, generated by the GFR, in a dynamic range of $10^6=(10^3)^2$. On the other hand, a limitation of maximal flow impedance of the GFR at about 150Pa·s/l, established by contemporary spirometry standards (American Thoracic Society Standards for Spirometry), restricts the maximal generated back-pressure to $(150\text{Pa}\cdot\text{s/l})\times(15\text{l/s})\approx 2\text{kPa}$. Therefore the minimum detectable differential pressure of the pressure transducer should be at the level of a few mPa. This requirement, combined with the necessity to operate in a dynamic range of six orders of magnitude, is a serious challenge for differential pressure transducers. Medical Graphics Corp. proposed a flowmeter containing two differential pressure sensors with an overlapping operating range of six orders of magnitude having a special sensor activated at low flows [US Patent 5038773]. The electronic

module of this spirometer has a sophisticated structure and contains sub-modules providing analog signal conversion before being digitized by an analog-to-digital converter (ADC).

Usage of thermoanemometer-type transducers connected in parallel
5 to the GFR for flow measurements has been reported earlier [U.Bonne,
K.Fritsch, "Mikroanemometer für die Durchflußmessung von Gasen,"
Technisches Messen, 1994, v.61, n.7, pp.285-294; T.R.Ohnstein,
R.G.Johnson, R.E.Higashi, D.W.Burns, J.O.Holmen, E.A.Satren,
G.M.Johnson, R.E.Bicking, S.D.Johnson, "Environmentally Rugged, Wide
10 Dynamic Range Microstructure Airflow Sensor," Proceedings on Solid-
State Sensors and Actuators Conference (1990), pp.158-160]. One
particular thermoanemometer-type transducer has a linear operating range
of about four orders of magnitude and total operating range of more than
six orders of magnitude [Frolov G.A., Gendin A.V., Grudin O.M., Katsan I.I.,
15 Krivoblotskiy S.N., Lupina B.I, "Micromechanical thermal sensors for gas
parameters measurements," Proceedings of 1996 ASME International
Engineering Congress and Exposition, DSC-Vol.59, Micro-electro-
mechanical systems, pp. 61-65]. This particular transducer covers the
whole operating range that makes it attractive for usage in flowmeters.
20 Another advantage of thermoanemometer-type sensors is that their
resolution can be improved to a level as fine as several mPa without
degrading their dynamic properties. For example, the response time of the
mass flow AWM-series sensors manufactured by Honeywell Inc., with
resolution mentioned above, is about 3ms.

25 A thermoanemometer-type transducer contains a functional element
sensitive to gas flow passing through a specially designed gas flow
assembly [US Patent 4548078]. This gas flow is proportional to pressure
drop across the transducer, which makes it also possible to use it also for
differential pressure measurements. The physical principle of gas flow
30 measurement is based on flow-induced disturbance of a symmetrical
temperature distribution in the gas around a heater. This disturbance,

caused by the shift of the heated volume of gas in the direction of flow, is usually detected by a pair of temperature-sensitive elements. Typically, the flow-sensitive element contains one or two heaters, which warm the gas in a certain region of the flow channel. It also includes at least two

5 temperature-sensitive elements detecting distortion of the temperature distribution in the heated volume of gas. The functions of gas heating and temperature sensing can be separated, for example, as in the sensor with the central heater and two temperature-sensing elements on opposite sides of the heater [US Patent 4548078]. In an other design, the flow sensor may

10 use only two self-heated temperature-sensing elements, which warm the gas and measure the temperature difference simultaneously [H-E. de Bree, P. Leussink, T. Korthorst, H. Jansen, T S J. Lammerink, M. Elwenspoek, "The μ -flown: A novel device for measuring acoustic flows," Sensors and Actuators A (1996), v.54, n.1, pp.552-557]. The differences between such

15 designs are not sufficient for subsequent consideration in this document.

Thermoanemometer-type flow or differential pressure transducers are sensitive to acceleration acting in the direction parallel to the gas flow in the transducer flow channel. This effect, caused by the shift of the heated volume of gas having lower density than the surrounding colder gas, results

20 in a temperature difference sensed by the two temperature-sensitive elements. Acceleration applied in directions perpendicular to the gas flow also causes shift of the heated volume of gas, but this shift is in a direction which does not significantly change the temperature difference measured at the two temperature-sensitive elements. Therefore the transducer has

25 low sensitivity to acceleration perpendicular to gas flow. In general, in a single sensor, the acceleration-induced output signal is indistinguishable from a flow-induced signal. Sensitivity to acceleration of the considered differential pressure transducers adversely affects the accuracy of the transducers and hence the gas flowmeter exposed to mechanical

30 disturbances such as vibrations, rotation and displacement.

Another problem is also caused by the necessity to detect and process differential pressure signals approximately 1000 times lower than those generated by near-linear GFRs (for example, Fleisch- or Lilly-type tubes in spirometry). During flowmeter operation (for example, spirometry testing), some vibrations or shocks of the device parts, such as the pneumatic hoses connecting the GFR with differential pressure sensor, may occur. Being negligibly small with respect to differential pressure signals generated by linear GFRs, these parasitic signals may nevertheless be significant compared to useful signals generated by nonlinear GFRs. Interference by spurious signals such as these, reduces the accuracy of the flowmeter. Immunity to these vibrations is considered to be an important feature of the flowmeter especially for compact hand-held versions of the instrument. Signal filtering techniques to suppress parasitic signals can be used, as long as they do not violate any standards in the field of application. For example, spirometry standards define a speed of response required to measure flow parameters of the patient's respiration which should be maintained by any spirometer.

A flowmeter containing two nonlinear functional elements, such as the GFR and thermoanemometer-type sensor, has a complex and essentially nonlinear conversion characteristic from flow to output voltage, which must be linearized. To linearize the flowmeter, its calibration curve $F(V)$, which specifies the correspondence between the flow F and the measured voltage V , must be defined. The present invention addresses also linearization of an essentially nonlinear flowmeter, containing a GFR with flow-resistive element generating differential pressure close to the square of the flow.

Contemporary spirometers typically contain analog-to-digital converters (ADC), digitizing analog signals from the transducer for subsequent processing. To provide the required resolution in the wide operating range of almost six orders of magnitude mentioned above, an ADC with resolution higher than 16-18 bits should be used. Meanwhile,

comparatively cheap, simple and widespread 12-bit ADCs are preferable. Therefore the problem of resolving of low flows (in the flowmeter with nonlinear GFR), arises not only from the restricted sensitivity of differential pressure transducers, but also from the limited resolution of the preferred
5 electronic circuitry.

Summary of the Invention

It is an object of the present invention to provide the following solutions:

- 10 • Improve effectiveness of the GFR by increasing its (differential pressure)-to-(back pressure) ratio;
- Simplify the shape of the GFR for better reproducibility and easier manufacturing;
- 15 • Improve immunity of the flowmeter to vibrations or shocks of the device and its parts, including the thermoanemometer-type differential pressure and flow transducers.
- Improve resolution and hence accuracy of the flowmeter at low flows;
- Accurate linearization of the gas flowmeter.

1. One of the goals of the invention is solved by the new design of the flow-
20 resistive element of the GFR. The flow-resistive element is made in the form of an obstacle to gas flow having non-symmetrical shape when viewed along the long axis of the GFR tube. The flow-resistive element is designed to simultaneously obtain low overall back-pressure, and high local differential pressure measured between two points inside the GFR. The
25 local differential pressure is created by placing an obstacle in the GFR, directly between the two points inside the GFR at which the differential pressure is measured, typically, in the case of bi-directional flow measurement, as close as possible to the midpoint of the line connecting these two points.

According to a broad aspect of this feature, there is provided a gas flow receiver comprising a flow tube having a sidewall and guiding flow therethrough while inducing minimal resistance, an upstream sensing tube having an upstream orifice communicating with the flow tube via the sidewall, and a downstream sensing tube having a downstream orifice communicating with the flow tube via the sidewall. The receiver also has a non-symmetrical-flow-inducing diaphragm mounted in the flow tube between the upstream and the downstream orifices, and causing non-symmetrical flow in the flow tube with an accentuated higher pressure near the upstream orifice than would be sensed in a corresponding cross-section of the flow tube and an accentuated lower pressure near the downstream orifice than would be sensed in a corresponding cross-section of the flow tube, the orifices being positioned with respect to the diaphragm so as to sense accentuated pressure substantially without sensing pressure oscillations due to any turbulence induced by the diaphragm.

Preferably, the diaphragm is mounted to the sidewall between the orifices. The diaphragm may be shaped so as to exhibit high drag and generate maximum accentuated pressure for its size. The flow tube may have a smaller cross-section between the orifices and may be similarly tapered on both sides of the small cross-section.

2. To improve immunity to vibrations of the thermoanemometer-type differential pressure transducer, two or more thermoanemometer-type flow-sensitive elements are connected and used such that the parasitic acceleration-induced components of the signals can be separated from the flow-induced components, and cancelled, thus allowing identification of the flow-induced signals.

In general, this can be accomplished by using a plurality of flow-sensitive elements connected in such a way that flow and acceleration act in different directions (angles) at different flow-sensitive elements. Many

different embodiments are possible. For example, two thermoanemometer-type flow-sensitive elements are connected in a specific way, such that the gas flows through each of the elements in opposite directions. The output signals of the two flow-sensitive elements are processed electronically so
5 that the acceleration-induced components of the signals are cancelled, while flow-induced components of the signals are doubled.

Another combination may also include at least one flow-sensitive element through which no gas flows. Being subjected to the applied acceleration, this reference element generates an output signal which is
10 used to cancel the acceleration-induced component of the element through which the gas flows.

According to a broad aspect of this feature, there is provided a gas flow transducer apparatus with immunity to vibration or acceleration, which comprises a plurality of gas flow transducer elements each sensitive to
15 vibration or acceleration in at least one direction and generating an output signal proportional to gas flow and to a perturbation component resulting from the vibration or acceleration. The transducer elements are arranged on a common support and a plurality of gas flow passages leading gas flow from an inlet to an outlet through at least one of the transducer elements.
20 The elements are arranged on the common support and connected to the passages such that at least one of the perturbation component and the gas flow is measured differently by the transducer elements. Circuitry is provided that receives the output signal of each of the transducer elements and outputs a vibration or acceleration immune output signal corresponding
25 to the gas flow with the perturbation component substantially cancelled.

The gas flow passages may cause the gas flow to be equal through the transducer elements, and the gas flow may be split between the transducer elements, or it may pass serially through the transducer elements. Preferably, two transducer elements are provided that are
30 sensitive to vibration or acceleration along only one axis and are arranged

parallel to one another, the gas flow passages being arranged such that the gas flow is in opposite directions through the transducer elements.

Gas flow may be blocked in at least one of the transducer elements, wherein the at least one of the transducer elements measures only the
5 perturbation component.

Preferably, the at least one of the transducer elements communicates with the gas flow such that the at least one of the transducer elements is subjected to a same gas composition and temperature as other ones of the transducer elements.

10 The transducer elements preferably comprise thermoanemometer-type transducers.

3. To enhance flowmeter resolution at low flows, which would otherwise be limited by the quantization noise of ADC, the following signal processing is
15 proposed.

Option 1.

- 3.1) The output analog signal of the differential pressure transducer should have high frequency components at frequencies $f > 1/\Delta t$, where Δt is the ADC sampling rate, where the amplitude of these
20 high-frequency components must exceed one quantization unit of the ADC;
- 3.2) If the output analog signal of the differential pressure transducer does not have high frequency components at frequencies $f > 1/\Delta t$ with amplitude exceeding one quantization unit of the ADC, then an
25 artificially-generated oscillating signal, or noise, meeting this criteria should be mixed with the signal prior to digitizing by the ADC;
- 3.3) The average output signal voltage is calculated by arithmetic averaging of several samples from the output of the ADC, during a

time $\tau = N \cdot \Delta t$, where $N > 2$, resulting in resolution better than the quantization unit of the ADC;

- 3.4) The flow corresponding to averaged signal voltage from 3.3) is calculated from the calibration curve of the flowmeter;

5

Option 2. The output analog signal of the differential pressure transducer, as specified above in 3.1)-3.2), can be further processed as follows:

- 3.5) The flow corresponding to the digitized output signal voltage sample is calculated from the calibration curve of the flowmeter;

- 10 3.6) The averaged flow is calculated during time $\tau = N \cdot \Delta t$, where $N > 2$.

According to a broad aspect of this feature, there is provided a method of estimating a value of an analog signal using an analog-to-digital converter (ADC) with a level of precision greater than a minimum quantization value of the ADC. The method comprises:

- 15 adding a secondary signal to the analog signal, the secondary signal having a zero DC component, a substantially even and symmetric amplitude distribution and a peak-to-peak amplitude greater than the minimum quantization value;

recording and storing a digital output value of the ADC;

- 20 averaging the digital output value recorded over a sampling period to obtain an estimated higher precision digital value with a precision greater than a precision of the digital output value.

- Preferably, the secondary signal is provided by noise generated in amplifier circuitry used to amplify the analog signal, and the analog signal
25 may be a gas flow transducer signal in addition to other types of signal.

Preferably, the sampling period varies as a function of an amplitude of the analog signal, wherein the sampling period is longer for lower amplitude values and is shorter for higher amplitude values.

4. To suppress parasitic signals due to vibrations or shocks of the flowmeter or its parts, without degrading the frequency response of the device, the output analog signal of the differential pressure transducer, conditioned with high-frequency components as specified in 3.1)-3.2), can
5 be processed as follows:

4.1) The whole operating range of the flowmeter is divided into at least 2 (preferably more) non-overlapping sub-ranges. The number of sub-ranges can be theoretically up to the number of quantization units in the ADC. The averaging times can then be different for each sub-range;
10

4.2) When flow is measured in accord with 3.3), 3.4) or 3.5) above, the averaging times must monotonically decrease from low-flow sub-range(s) to high-flow sub-range(s).

According to a broad aspect of this feature, there is provided a
15 method of filtering a signal comprising the steps of measuring an amplitude of the signal, determining an averaging period τ as a function of the amplitude, wherein τ is longer for lower values of the amplitude and τ is shorter for higher values of the amplitude, and averaging the amplitude over the period to provide a filtered output signal.

20 The function may be a step function. When the amplitude is above a predetermined threshold, the filtered output signal may be the instantaneous value of the amplitude. Preferably, the step of measuring comprises converting an analog gas flow transducer signal to a digital signal providing the amplitude.

25

5. The general type of the calibration function, $F(V)$, of the flowmeter containing flow-resistive element generating differential pressure close to the square of flow, is invented:

$$F(V) = \sum_{i=1}^N A_i V^{\frac{i}{\alpha_i}}$$

where N is equal or greater than 3; parameters $\alpha_i > 1$ (preferable values of α_i are close to 2); and A_i are coefficients determined experimentally for a particular flowmeter, to give the best linearization results. For higher
 5 accuracy, the whole operating range of the flowmeter is divided into several (at least two) sub-ranges, and a calibration function is found separately for each of the sub-ranges by the same method.

According to a broad aspect of this feature, there is provided a method of processing a transducer output signal that is non-linear with
 10 respect to a physical parameter being measured to obtain a calibrated output signal representing the physical parameter on a given scale. The method comprises:

- subjecting the transducer to a number of calibrated physical parameter conditions;
- 15 recording a value of the output under each of the conditions;
- obtaining an analytical solution for a non-linear function relating the output value to the physical parameter, the solution being expressed as:

$$F(V) = \sum_{i=1}^N A_i V^{\frac{i}{\alpha_i}}$$

where V is the transducer output signal; N is greater than or equal to 3;
 20 parameters A_i are coefficients determined from the recorded values; α_i are real numbers;

determining the calibrated output signal for the transducer output signal using the analytical solution.

Preferably α_i are greater than 1, and may be non-integers.

25 The step of determining may comprise:

calculating a value of the physical parameter for each possible value of the transducer output signal using the analytical solution; and

building a table of the physical parameter values indexed by digital output values;

5 converting the transducer output signal into a digital output value; and

obtaining a value of the calibrated output signal from the table using the digital output value.

10 The analytical solution may be exact for each of the recorded values, and the analytical function may be divided into subranges.

The transducer output signal may be derived from a gas flow transducer signal having a square transfer function, and the gas flow transducer is preferably a thermoanemometer-type transducer apparatus.

15 **Brief Description of the Drawings**

The invention will be better understood by way of the following, non-limiting, detailed description of a preferred embodiment and alternate embodiments with reference to the appended drawings, in which:

20 Fig. 1 is a schematic of the flowmeter containing the Gas Flow Receiver, differential pressure transducer, analog electronic module and ADC module;

Fig. 2 is the Gas Flow Receiver with star-like diaphragm (prior art);

Fig. 3 is the Gas Flow Receiver with the invented non-symmetrical flow-resistive element;

25 Fig. 4 shows the measured back-pressure versus flow for both types of the GFRs;

Fig. 5 shows the measured ratio η of differential pressures generated by non-symmetrical and symmetrical flow resistive elements versus flow;

Fig. 6 shows deviations of experimentally-measured syringe volume from its actual value obtained during "expiration" and "inspiration", at different averaged flow rates for the GFR with symmetrical star-like obstacle;

- 5 Fig. 7 shows deviations of experimentally-measured syringe volume from its actual value obtained during "expiration" and "inspiration," at different averaged flow rates for the GFR with invented non-symmetrical flow-resistive element;

Fig. 8 is a schematic side view of the GFRs;

- 10 Fig. 9 is a schematic front view of the flow resistive element within the GFR tube (viewed along the long axis of the tube);

- Figs. 10 and 11 show the configuration of the invented differential pressure and flow transducer containing two thermoanemometer-type flow-sensitive elements. The channel for flowing gas connects two elements in series (Fig. 10), or in parallel (Fig. 11);

- 15 Fig. 12 depicts a schematic of a single flow-sensitive element with acceleration applied to it;

Fig. 13 shows an example of a more complex configuration involving three flow-sensitive elements connected in a triangle;

- 20 Fig. 14 shows the configuration of two identically-aligned flow-sensitive elements with flow passing through only one of them;

Fig. 15 shows (a) unfiltered, and (b) filtered output signals of the flowmeter at low flows;

Fig. 16 is a block-diagram of the electronic module of the flowmeter;

- 25 Figs. 17 and 18 are flow charts describing the invented signal processing;

Fig. 19 shows the reaction of the flowmeter to a flow impulse; and
Fig. 20 shows a calibration curve of the flowmeter.

Description of the Preferred Embodiment

In the preferred embodiment, a gas flow receiver has a non-symmetrical-flow-inducing diaphragm mounted in a flow tube and causes non-symmetrical flow in the flow tube with an accentuated higher pressure
5 near an upstream orifice than would be sensed in a corresponding cross-section of the flow tube and an accentuated lower pressure near a downstream orifice. A gas flowmeter using thermoanemometer-type transducers receiving gas flow from the upstream orifice is made immune to vibration or acceleration, for example, by arranging a pair of the
10 transducers parallel to one another with the gas flow passing serially through them, but in opposite directions. The resulting transducer signals processed to cancel the effect of the vibration or acceleration. The transducer output is amplified by a noisy amplifier which injects a secondary signal prior to digital conversion using an ADC. The digital signal
15 is averaged over a sampling period to obtain a sample having a level of precision greater than a minimum quantization value of the ADC. The sampling period is varied as a function of the transducer's analog signal amplitude, such that the sampling period is longer for lower amplitude values and is shorter for higher amplitude values. The sampling period
20 variation provides signal filtering. Since the flowmeter has a non-linear response, a calibrated output signal representing flow is obtained by recording samples under a number of calibrated flows and obtaining an analytical solution for the non-linear function, using the analytical solution to obtain calibrated values for all sample values, and, in operation, looking up
25 a calibrated value corresponding to a sample value. Having briefly described the features of the preferred embodiment together, the individual features will now be described hereinbelow in greater detail.

The present application describes a variety of inventive features applicable to a gas flowmeter. These features improve the characteristics
30 of the flowmeter. Maximum effectiveness of the improvement can be

reached when the inventions discussed below are implemented jointly and are therefore presented together herein.

TUBE FOR CONVERSION OF GAS FLOW TO DIFFERENTIAL PRESSURE

5

Fig. 1 shows a schematic view of the flowmeter containing GFR 1, differential pressure transducer 2, analog electronic module 3 and ADC module 4. The flow-resistive element 5 of the invented gas flow receiver (GFR) 1 is designed to simultaneously obtain low overall back-pressure, and high local differential pressure measured between two points inside the GFR 1 for bi-directional flow measurement, for example in spirometry. The local differential pressure is created by placing an obstacle 5 in the GFR 1, directly between the two points inside the GFR 1 at which the differential pressure is measured, as close as possible to the midpoint of the line connecting these two points. In some circumstances, it may be desirable for the obstacle or diaphragm to be positioned offset from the midpoint.

10

To prove the invented idea, two experimental GFRs have been constructed. Each of the star-like symmetrical diaphragm 7 and the invented non-symmetrical diaphragm 5 were placed in the middle of identical tubes 120mm long with input inner diameter of 21mm and inner diameter of 19mm at the center of the tube (Figs. 2 and 3). The shapes of the flow-resistive elements have been chosen so as to generate back pressure lower than 150Pa·s/l (required by ATS standards for spirometry). The six beams of the star-like diaphragm 7 have width of 1mm each. The central spot of the diaphragm has a diameter of 4mm. The non-symmetrical diaphragm 5 has the shape of a circular segment with height of 4mm. The star-like diaphragm 7 has thickness of 1mm while the segment-type diaphragm 5 has a thickness of 0.1-0.2mm.

20

25

Each of the GFRs was connected to the same differential pressure transducer 2 and individually calibrated. Back pressure was measured by

30

an additional pressure sensor. A 3-liter calibration syringe called "SpiroCal" manufactured by Burdick Inc. (Milton, WI, USA), was used to generate gas flows during the experiments. Fig. 4 shows the dependence of back pressure on air flow, for the two GFRs. Fig. 5 depicts the ratio $\eta = \Delta P_1 / \Delta P_2$ as function of flow, where ΔP_1 and ΔP_2 are differential pressures generated by the GFRs with the invented non-symmetrical diaphragm 5, and symmetrical star-like diaphragm 7, respectively. The invented GFR generates lower back pressure and higher differential pressure than the GFR with symmetrical diaphragm 7.

10 To check the sensitivity of the two tubes to gas velocity distribution across the cross-section of the tube, the following two-step experiment was performed. In the first step, each tube (after calibration) was connected to the syringe, and gas was "inspired" from the ambient through the tube into the syringe by piston strokes at different flow rates – "inspiration". The inspired volume was measured by integrating flow measurements over time, and compared with the actual volume of the syringe. In the second step, each tube was rotated by 180 degrees, such that its flow direction was reversed, and connected to the syringe with its opposite end, and the same experiments were conducted except with gas being pumped out of the syringe, by "expiration" piston strokes. Thus, the direction of gas flow in the tubes was the same, but the connections, and thus, the gas flow velocity distributions in the flux, were different. In the first step, the GFR input is connected directly to an infinite volume of ambient gas, while in the second step the gas flux entering the GFR is shaped by a 40mm-long connecting tube with inner diameter of 30mm. Deviations (in %) of experimentally measured syringe volume from its actual value, obtained in the regimes "expiration" and "inspiration" at different averaged flows, for the two tested GFRs, are presented in Figs. 6 and 7. The GFR with the star-like diaphragm 7 demonstrated a discrepancy in measured volumes up to 8.5% due to changes of its orientation, which confirms its sensitivity to gas velocity distribution across the cross-section of the tube. For the invented

tube, these discrepancies did not exceed 1%, which demonstrates substantially lower sensitivity to gas velocity distribution across the cross-section of the tube.

5 The invented GFR has a simpler shape than the GFR with symmetrical star-like diaphragm or crest-type flow resistive element. This can simplify its manufacturing and improve reproducibility of the conversion characteristic.

10 The described embodiment confirms the advantages of the invented solution. Meanwhile, other shapes of non-symmetrical flow-resistive element can be used according to the invention. GFRs containing the invented flow-resistive elements in the form of non-symmetrical circular segments with heights of 3mm and 5mm, have been also tested. Experimental results are shown in Figs. 4 and 5, represented by circular and triangular symbols, respectively. These variations have also
15 demonstrated low sensitivity to gas velocity distribution across the cross-section of the tube.

An increase of the thickness of the circular segment obstacle from 0.2mm to 1-2mm does not cause significant changes in the conversion characteristics of the GFR. Observed deviations of back-pressure and local
20 differential pressure did not exceed 5%.

Figs. 8 and 9 show several possible designs of the GFR, which do not exhaust all possible shapes of the GFRs. The particular choice of GFR should be made to provide optimal adaptation to the given application and manufacturing techniques. In Fig. 8, different cross-sections of flow-resistive element 8, 9, 10 are shown inside the GFR 1. The GFR 1 may
25 also contain tubing 11 attached at a certain angle. Front views of plane diaphragms 12, 13, 14 used as flow-resistive elements are shown in Fig. 9.

In the preferred embodiment, the flow measured is bi-directional. In the case that the flow is in one direction, the positioning of the non-

symmetrical diaphragm may preferably be in a position different from the midpoint between the sensing tube orifices.

DIFFERENTIAL PRESSURE AND GAS FLOW TRANSDUCER WITH IMMUNITY TO VIBRATIONS/ACCELERATION

Figs. 10 and 11 show two possible configurations of the invented transducer, where two flow-sensitive elements **15** are connected in series (Fig. 10), and in parallel (Fig. 11). In both cases, the gas flowing through the channels passes through the flow-sensitive elements in opposite directions. Therefore, the heated volumes of gas **16** near the heaters **17** in both flow-sensitive elements **15** (shown as shaded circles), are also shifted in opposite directions causing inverted output signal components. When acceleration is applied in the direction parallel to gas flow as shown on Fig. 12, heated volumes of gas **16** are shifted in the same direction for both flow-sensitive elements **15** causing increments in output signals which are the same for both sensors. The output signals $V_{sensor1}$ and $V_{sensor2}$ of the two flow-sensitive elements **15** are then processed by electronic circuitry **3**, such that one signal is subtracted from the other. The following three equations summarize the situation.

$$\begin{aligned} V_{sensor1} &= V_{flow} + V_{acceleration} \\ V_{sensor2} &= -V_{flow} + V_{acceleration} \\ V_{sensor1} - V_{sensor2} &= 2 \cdot V_{flow} , \end{aligned}$$

where V_{flow} and $V_{acceleration}$ are the sensor output voltage components caused by gas flow and applied acceleration, respectively.

If the two linear flow-sensitive elements **15** are identical, sensitivity to acceleration of the whole transducer can be reduced theoretically to zero. In practice, the immunity to acceleration may be limited by mismatch of the two sensor elements **15** and calibration of their sensitivities.

The choice of schemes presented in Figs. 10 and 11 depends on the particular application. The transducer with two flow-sensitive elements **15**

connected in series has flow impedance two times higher than a single element, while the second transducer (Fig. 11) has flow impedance two times lower.

For experimental verification of the invented concept, a prototype of the transducer was assembled on the basis of two AWM2200 mass flow sensors (Honeywell) connected in series by plastic hoses. The performance of the assembled prototype was compared with the performance of a single AWM2200 sensor. The electronic circuitries of the transducers provided the same sensitivity to differential pressure. Then both devices were rotated in the Earth's gravity. The single AWM2200 sensor has sensitivity to acceleration of 14mV/g while the prototype of the invented transducer is completely immune to the same acceleration within the resolution of the electronic circuitry (less than 1mV). Both tested transducers have the same sensitivity to gas flow.

The invented configuration of the transducer 2, immune to acceleration, can be realized by a variety of methods. The best results may be obtained by the usage of identical flow-sensitive elements. These flow-sensitive elements may be commercially available sensors as described above or specially designed functional sensing elements.

Among other possible configurations, one is shown in Fig. 13, where three flow-sensitive elements are arranged in the same plane and connected in the shape of a triangle. In this case, the output signals of each flow-sensitive element can be written as:

$$\begin{aligned} V_{\text{sensor1}} &= V_{\text{flow}} + V_{\text{acceleration}} \cos(60^\circ - \beta) \\ V_{\text{sensor2}} &= V_{\text{flow}} + V_{\text{acceleration}} \cos(60^\circ + \beta) \\ V_{\text{sensor3}} &= -V_{\text{flow}} - V_{\text{acceleration}} \cos(\beta) \end{aligned}$$

where β is the effective angle of the acceleration, as shown in Fig. 13.

This system of three equations with three unknown parameters, V_{flow} , $V_{\text{acceleration}}$ and β , can be solved to cancel the influence of the acceleration-induced component of the signal.

Fig. 14 depicts another possible combination of two flow-sensitive elements. The gas passage 18, which is opened to the main gas passageway at one end allows the reference sensor to experience the same gas composition, pressure and temperature, without experiencing the gas flow. When conditions of gas composition, pressure and temperature are constant, sensor 2 may be isolated without using the passage 18. In this case, the following three equations summarize the sensors output signals and the obtaining of the flow signal. The output signals of the sensors are:

$$\begin{aligned} V_{\text{sensor1}} &= V_{\text{flow}} + V_{\text{acceleration}} \\ V_{\text{sensor2}} &= V_{\text{acceleration}} \\ V_{\text{sensor1}} - V_{\text{sensor2}} &= V_{\text{flow}} \end{aligned}$$

Processing of the output signals can thus cancel the acceleration-induced component of the signal.

The following points should be noted:

In addition to the described acceleration compensation, compensation for variations in temperature, gas composition and ambient pressure also may be implemented in ways typically used in mass-flow controllers. Meanwhile, the invented acceleration suppression is effective independently of the particular embodiment shown in Figs. 10, 11, 13, 14 and independent of the method of possible compensation of gas temperature, gas composition and ambient pressure.

SIGNAL PROCESSING FOR IMPROVEMENT OF FLOWMETER ACCURACY.

The invented method to improve flowmeter resolution at low flows (which would otherwise limited by quantization noise of the ADC, unless one is ready to use a high-resolution ADC), by special signal processing was experimentally checked with a flowmeter containing a nonlinear GFR 1, described above, and mass flow sensor AWM2200, manufactured by

Honeywell Inc. and connected to the GFR 1 by two plastic hoses 6. Sensor excitation and signal amplification was performed by the circuitry recommended by the manufacturer. The severe decrease of the flowmeter sensitivity at low flows results from the near-square-law dependence of differential pressure versus flow generated by the GFR 1. The limited resolution of the ADC 4 restricts minimal detectable flow. At the same time, parasitic vibration-caused signals are large enough to degrade accuracy of the flowmeter at low flows. As an example, Fig. 15a shows the influence of the intentionally generated vibrations of the pneumatic hoses 6. The minimum detectable flow defined by the resolution of the ADC 4 (flow corresponding to +1mV or -1mV, the quantization unit of the ADC) was found to be approximately 50ml/s (without the invented signal processing). In the described experiment, the electronic module contained a typical 12-bit ADC 4 (AD7890-4). The digitized signal, with sampling rate $\Delta t = 2\text{ms}$, was transferred to a personal computer for visualization, storage and processing.

The reasonable useful frequency bandwidth of the electronic module for the detection of variable flows, specified by the ATS standards, need not be greater than 100-150Hz. To artificially increase the high-frequency noise component of the analog output signal in accord with the invention (as specified above in 3.2)), the frequency bandwidth of the electronic module was intentionally increased up to 10kHz. The increased high-frequency noise component of the analog output signal, determined by approximately white noise of the operational amplifiers of the circuitry, had amplitude of approximately $\pm 3\text{mV}$, equivalent to three quantization units of the ADC 4. This added noise is shown in Fig. 15a. A schematic block-diagram of the device is shown in Fig. 16. In the described experimentally-checked embodiment, additional noise was generated inside the analog circuitry module.

- four sub-ranges are defined in terms of voltage (not flow);
- averaging is done with voltage transformed into digital format;

- resulting flow corresponding to averaged voltage is found from the calibration curve of the flowmeter.

While very important at low flows, the described filtering procedure may be redundant at higher flows because of the steep signal rise proportional to approximately the square of flow. For example, a rise of flow from 50ml/s to 2 l/s results in signal increase by a factor of $1600=40^2$ which is more than one order of magnitude higher than the usual parasitic signals due to vibrations. On the other hand, the high frequency response of the flowmeter is required mainly at high flows (for example, spirometry), which would be degraded by a long averaging time τ . Thus, the usage of several sub-ranges with low averaging times at high flows, maintains satisfactory speed of response at medium and high flows. Fig. 19 shows the reaction of the flowmeter to a flow impulse generated by a "SpiroCal" 3-liter syringe. At high flows, the filtered signal (b) has the same shape as the unfiltered signal (a). Its fall time is estimated to be less than 10ms. The effect of filtering at low flows can be recognized by the effective suppression of the oscillating acoustic signal generated by the collision of the piston with the syringe bottom.

The parameters of this filtering method, i.e. number of flow sub-ranges, averaging times and amplitude of the analog signal noise component, can be chosen to optimize the operation of the flowmeter for a particular application. The parameters of the investigated physical process resulting in this choice are: required frequency response and flow operating range of the flowmeter, and intensity and frequency spectrum of the parasitic signals to be suppressed.

METHOD FOR FLOWMETER LINEARIZATION.

Typically, calibration of the flowmeter involves the following steps:

- measuring of the flowmeter output voltage at several reference flows;

- calculation of an analytical function which fits the actual calibration curve of the flowmeter;
- storage of the analytical function as:
 - a table which gives unambiguous correspondence of all possible ADC readings to flow;
 - parameters of the analytical function which allow calculation of flow for each ADC reading during the flowmeter operation.

Usually, a high precision flow generator is used to calibrate the flowmeter at several reference flows. The number of these reference flows should not exceed 10-20. Otherwise the calibration procedure would be unacceptably long. On the other hand, even a 12-bit ADC which is typically used in flowmeters measures 4096 voltage levels in the operating range of the device. Therefore finding an analytical function which accurately fits the actual calibration curve of the flowmeter and allows determination of flows corresponding to all possible ADC readings, is critically important. Methods of curve fitting are well-known and are not considered here.

The type of analytical function $F(V)$ which gives optimal fitting for the described flowmeter is disclosed:

$$F(V) = \sum_{i=1}^N A_i V^{\frac{1}{\alpha_i}},$$

where V is the output voltage of the flowmeter; N is greater than or equal to 3; parameters A_i are coefficients determined experimentally; α_i are real numbers (not necessary integer), typically greater than 1.

For verification of the invented linearization method, a prototype flowmeter was used. The flow meter was based on the GFR 1 described above, containing the 120mm long tube with input inner diameter of 21mm and inner diameter of 19mm at the center of the tube. A planar non-symmetrical diaphragm 5 having the shape of a circular segment with height of 4mm (Fig. 3), was used as a flow-resistive element. This

diaphragm with thickness of 0.2mm was located at the center of the tube, and generated differential pressure close to the square of the flow (square transfer function). Mass flow sensor AWM2200 (Honeywell) was connected to the GFR 1 with two plastic hoses 6 to measure flow-induced differential pressure. The flowmeter also contained a 12-bit ADC AD7890-10 operating in the range $\pm 10V$.

In accordance with the invention, the operating flow range of the flowmeter was divided into two sub-ranges, 0 – 2 l/s and 2 – 15 l/s. The coefficients A_i of the calibration curve $F(V)$ were found for $N=5$ and $\alpha_i=2$.
 10 Two functions defined separately for the two sub-ranges are graphed in Fig. 20. After calibration, the calibration curve was stored in form of the table in a computer file.

For checking of the flowmeter accuracy, its GFR was connected to the "SpiroCal" 3-liter calibration syringe. Then, air was pumped in and out of the syringe with different flow rates by piston strokes. The expired and inspired air volumes were measured by the flowmeter and compared with the actual volume of the syringe. Deviations of these two volumes (in %) shown in Fig. 7, do not exceed 2%. This confirms that the accuracy of the flowmeter is within 2% or better, exceeding the requirements specified by the ATS standards for spirometry.

In practice, the choice of the parameters N and α_i may differ from those used in the example presented herein, depending on the applications. For example, the linearization procedure was also successfully tested with $N=6$, although the algorithm of finding of coefficients A_i was more complicated.

The parameters α_i can be chosen so as to give better fitting of the calculated calibration curve with actual flow response of the flowmeter. At low flows, the dominant contribution is given by the first element of the sum: $F(V) \approx A_1 V^{\frac{1}{\alpha_1}}$. Transforming this equation, one obtains $V \approx b F^{\alpha_1}$. In

this case, the parameter α_1 defines conversion from flow to output voltage at low flows, which mainly depends on the construction of the GFR 1. Usually, the GFR 1 with diaphragm-type flow-resistive elements 5 generates differential pressure which varies near to the square of flow (square transfer function). For these types of GFRs 1, $\alpha_1=2$ gives a reasonable approximation of the calibration curve. Nevertheless some deviations of the parameter α_1 as well as parameters α_i ($1 < i < N$) from the value of 2 are also included in the invented linearization method.

Depending on the accuracy requirements and flow operating range, 10 the number of sub-ranges may also vary from one to some number greater than two. This choice depends on the particular application.

CLAIMS

1. A gas flow transducer apparatus with immunity to vibration or acceleration, the apparatus comprising:

a plurality of gas flow transducer elements each sensitive to vibration or acceleration in at least one direction and generating an output signal proportional to gas flow and to a perturbation component resulting from said vibration or acceleration, said elements being arranged on a common support;

a plurality of gas flow passages leading gas flow from an inlet to an outlet through at least one of said elements;

said elements being arranged on said common support and connected to said passages such that at least one of said perturbation component and said gas flow is measured differently by said elements; and

circuitry receiving said output signal of each of said elements and outputting a vibration or acceleration immune output signal corresponding to said gas flow with said perturbation component substantially cancelled.

2. The apparatus as claimed in claim 1, wherein said gas flow passages cause said gas flow to be equal through said elements.

3. The apparatus as claimed in claim 2, wherein said gas flow is split between said elements.

4. The apparatus as claimed in claim 2, wherein said gas flow passes serially through said elements.

5. The apparatus as claimed in claim 4, wherein two said elements are provided that are sensitive to vibration or acceleration along only one axis and are arranged parallel to one another, said gas flow passages being arranged such that said gas flow is in opposite directions through said elements.

6. The apparatus as claimed in claim 1, further comprising a gas throughflow blocking member preventing gas flow in at least one of said elements, wherein said at least one of said elements measures only said perturbation component.

7. The apparatus as claimed in claim 6, wherein said at least one of said elements communicates with said gas flow such that said at least one of said elements is subjected to a same gas composition and temperature as other ones of said elements.

8. The apparatus as claimed in any one of claims 1 to 4, 6 and 7, wherein said elements are sensitive to vibration or acceleration along only one axis.

9. The apparatus as claimed in any one of claims 1 to 4, and 6 to 8, wherein said apparatus comprises two of said elements.

10. The apparatus as claimed in one of claims 1 to 9, wherein said elements comprise thermoanemometer-type transducers.

11. A gas flow receiver comprising:

- 30 -

a flow tube having a sidewall and guiding flow therethrough while inducing minimal resistance;

an upstream sensing tube having an upstream orifice communicating with said flow tube via said sidewall;

a downstream sensing tube having a downstream orifice communicating with said flow tube via said sidewall; and

a non-symmetrical-flow-inducing diaphragm mounted in said flow tube between said upstream and said downstream orifices, and causing non-symmetrical flow in said flow tube with an accentuated higher pressure near said upstream orifice than would be sensed in a corresponding cross-section of said flow tube and an accentuated lower pressure near said downstream orifice than would be sensed in a corresponding cross-section of said flow tube, said orifices being positioned with respect to said diaphragm so as to sense accentuated pressure substantially without sensing pressure oscillations due to any turbulence induced by said diaphragm.

12. The gas flow receiver as claimed in claim 11, wherein said diaphragm is mounted to said sidewall between said orifices.

13. The gas flow receiver as claimed in claim 11 or 12, wherein said diaphragm is shaped so as to exhibit high drag and generate maximum accentuated pressure for its size.

14. The gas flow receiver as claimed in claim 11, 12 or 13, wherein said flow tube has a smaller cross-section between said orifices and is similarly tapered on both sides of said small cross-section.

15. A method of estimating a value of an analog signal using an analog-to-digital converter (ADC) with a level of precision greater than a minimum quantization value of the ADC, the method comprising the steps of:

adding a secondary signal to said analog signal, said secondary signal having a zero DC component, a substantially even and symmetric amplitude distribution and a peak-to-peak amplitude greater than said minimum quantization value;

recording and storing a digital output value of the ADC;

averaging the digital output value recorded over a sampling period to obtain an estimated higher precision digital value with a precision greater than a precision of the digital output value.

16. The method as claimed in claim 15, wherein said secondary signal is provided by a noise signal.

17. The method as claimed in claim 16, wherein said noise signal is generated in amplifier circuitry used to amplify said analog signal.

18. The method as claimed in claim 15, 16 or 17, wherein said analog signal is a gas flow transducer signal, and said gas flow transducer is a thermoanemometer-type transducer apparatus.

19. The method as claimed in any one of claims 15 to 18, wherein said sampling period varies as a function of an amplitude of the analog signal, wherein said sampling period is longer for lower amplitude values and is shorter for higher amplitude values.

20. A method of filtering a signal comprising the steps of:
- measuring an amplitude of the signal;
 - determining an averaging period τ as a function of said amplitude, wherein τ is longer for lower values of said amplitude and τ is shorter for higher values of said amplitude; and
 - averaging said amplitude over said period to provide a filtered output signal.
21. The method as claimed in claim 20, wherein said function is a step function.
22. The method as claimed in claim 20 or 21, wherein when said amplitude is above a predetermined threshold, said filtered output signal is the instantaneous value of said amplitude.
23. The method as claimed in claim 20, 21 or 22, wherein said step of measuring comprises converting an analog gas flow transducer signal to a digital signal providing said amplitude.
24. The method as claimed in claim 23, wherein said gas flow transducer is a thermoanemometer-type transducer apparatus.
25. A method of processing a transducer output signal that is non-linear with respect to a physical parameter being measured to obtain a calibrated output signal representing the physical parameter on a given scale, the method comprising:

subjecting said transducer to a number of calibrated physical parameter conditions;

recording a value of said output under each of said conditions;

obtaining an analytical solution for a non-linear function relating said output value to said physical parameter, said solution being expressed as:

$$F(V) = \sum_{i=1}^N A_i V^{\frac{i}{\alpha_i}}$$

where V is the transducer output signal; N is greater than or equal to 3; parameters A_i are coefficients determined from said recorded values; α_i are real numbers;

determining said calibrated output signal for said transducer output signal using said analytical solution.

26. The method as claimed in claim 25, wherein α_i are greater than 1.

27. The method as claimed in claim 26, wherein α_i are non-integers.

28. The method as claimed in claim 25, 26 or 27, wherein said step of determining comprises:

calculating a value of said physical parameter for each possible value of said transducer output signal using said analytical solution; and

building a table of said physical parameter values indexed by digital output values;

converting said transducer output signal into a digital output value; and

obtaining a value of said calibrated output signal from said table using said digital output value.

29. The method as claimed in one of claims 25 to 28, wherein said analytical solution is exact for each of said recorded values.

30. The method as claimed in one of claims 25 to 29, wherein said analytical function is divided into subranges.

31. The method as claimed in one of claims 25 to 30, wherein said transducer output signal is derived from a gas flow transducer signal having at least one of a square and a near-square transfer function.

32. The method as claimed in claim 31, wherein said gas flow transducer is a thermoanemometer-type transducer apparatus.

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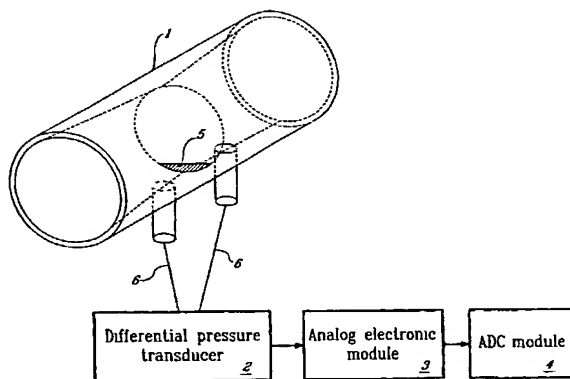
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[Continued on next page]

(54) Title: **GAS FLOW MEASURING APPARATUS AND SIGNAL PROCESSING METHODS APPLICABLE THERETO**



WO 01/18496 A2 (57) Abstract: A gas flow receiver has a non-symmetrical-flow-inducing diaphragm mounted in a flow tube and causes non-symmetrical flow in the flow tube with an accentuated higher pressure near an upstream orifice than would be sensed in a corresponding cross-section of the flow tube and an accentuated lower pressure near a downstream orifice. A gas flowmeter using thermoanemometer-type transducers receiving gas flow from the upstream orifice is made immune to vibration or acceleration, for example, by arranging a pair of the transducers parallel to one another with the gas flow passing serially through them, but in opposite directions. The resulting transducer signals processed to cancel the effect of the vibration or acceleration. The transducer output is amplified by a noisy amplifier which injects a secondary signal prior to digital conversion using an ADC. The digital signal is averaged over a sampling period to obtain a sample having a level of precision greater than a minimum quantization value of the ADC. The sampling period is varied as a function of the transducer's analog signal amplitude, such that the sampling period is longer for lower amplitude values and is shorter for higher amplitude values. The sampling period variation provides signal filtering. Since the flowmeter has a non-linear response, a calibrated output signal representing flow is obtained by recording samples under a number of calibrated flows and obtaining an analytical solution for the non-linear function, using the analytical solution to obtain calibrated values for all sample values, and, in operation, looking up a calibrated value corresponding to a sample value.

WO 01/18496 A2

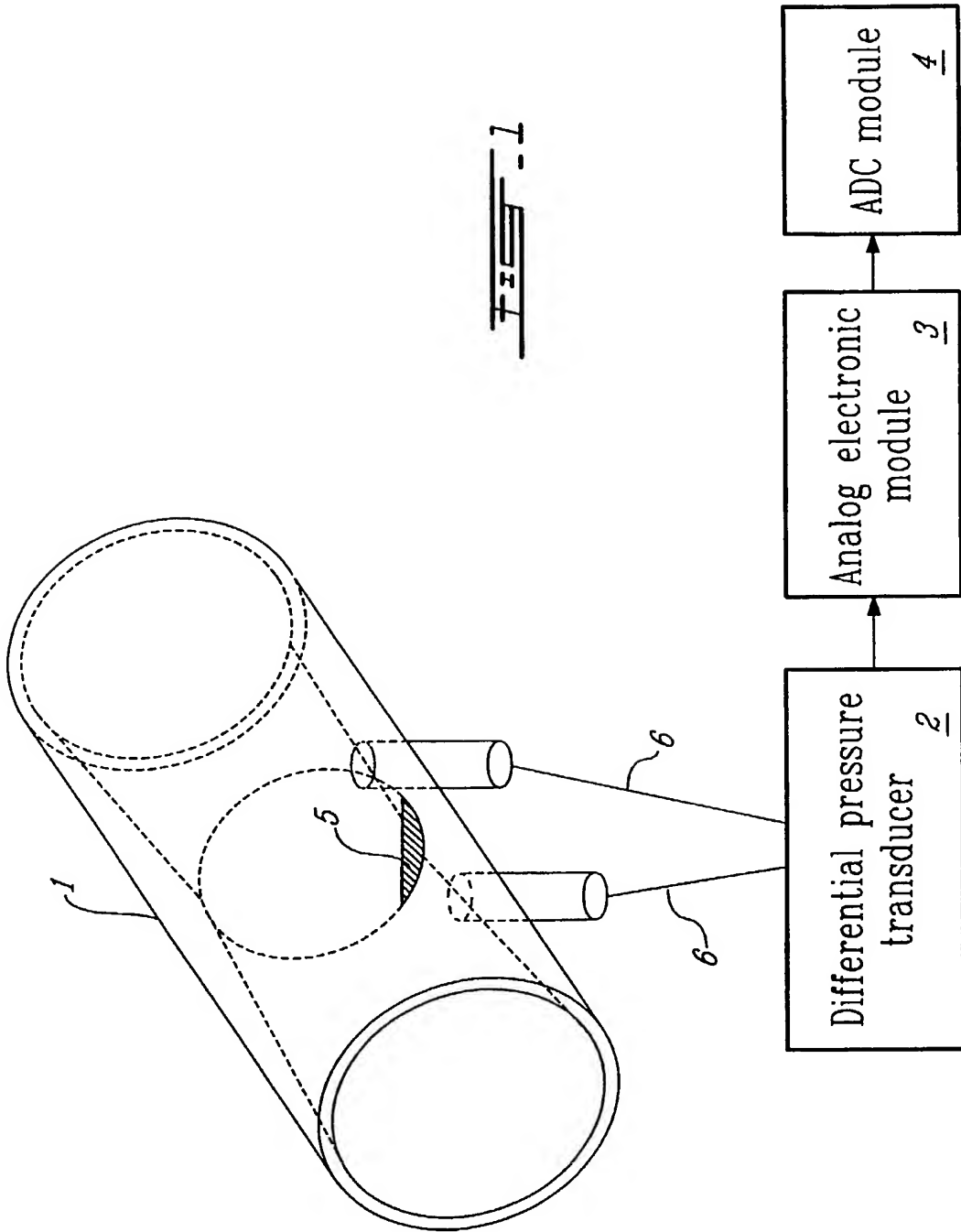


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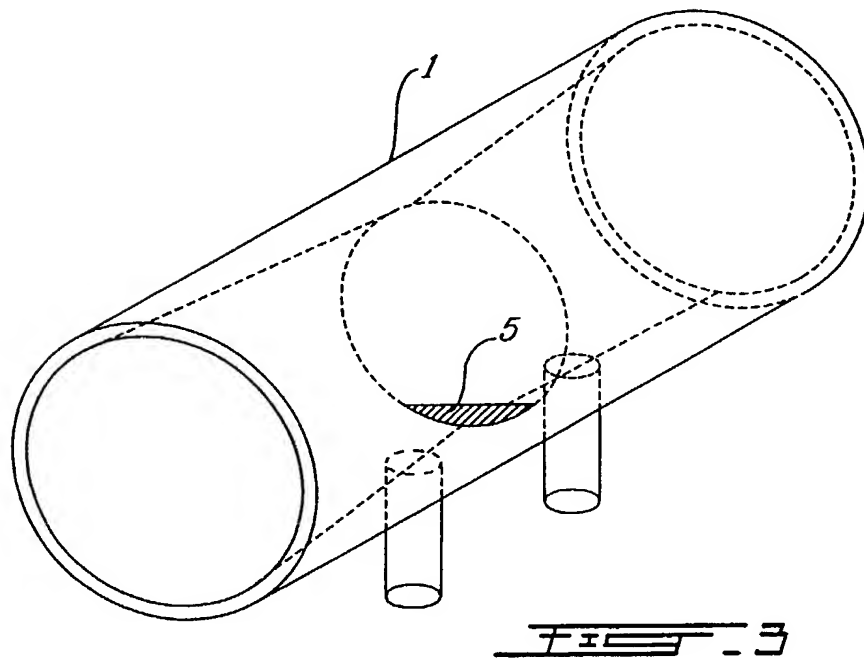
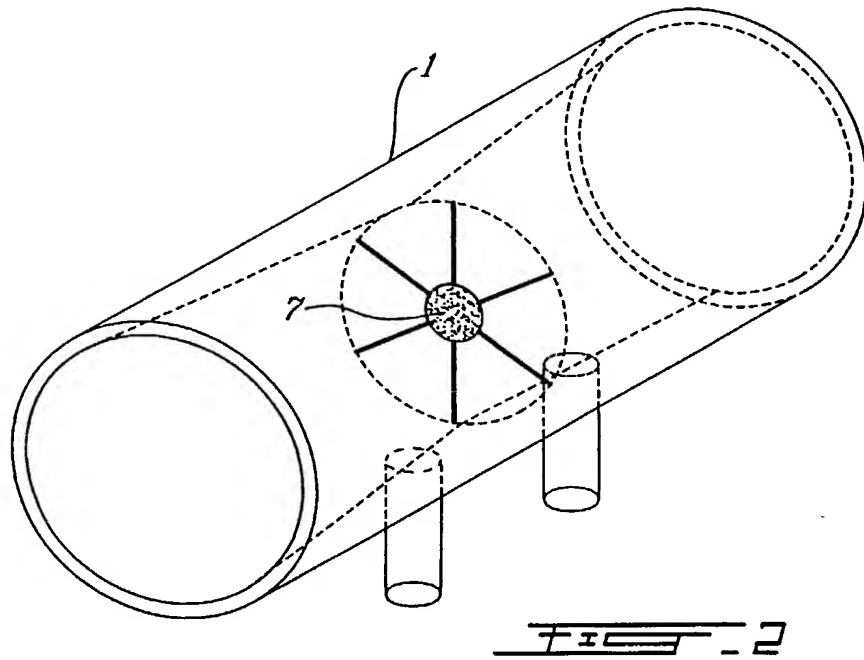
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1/16



2/16



3/16

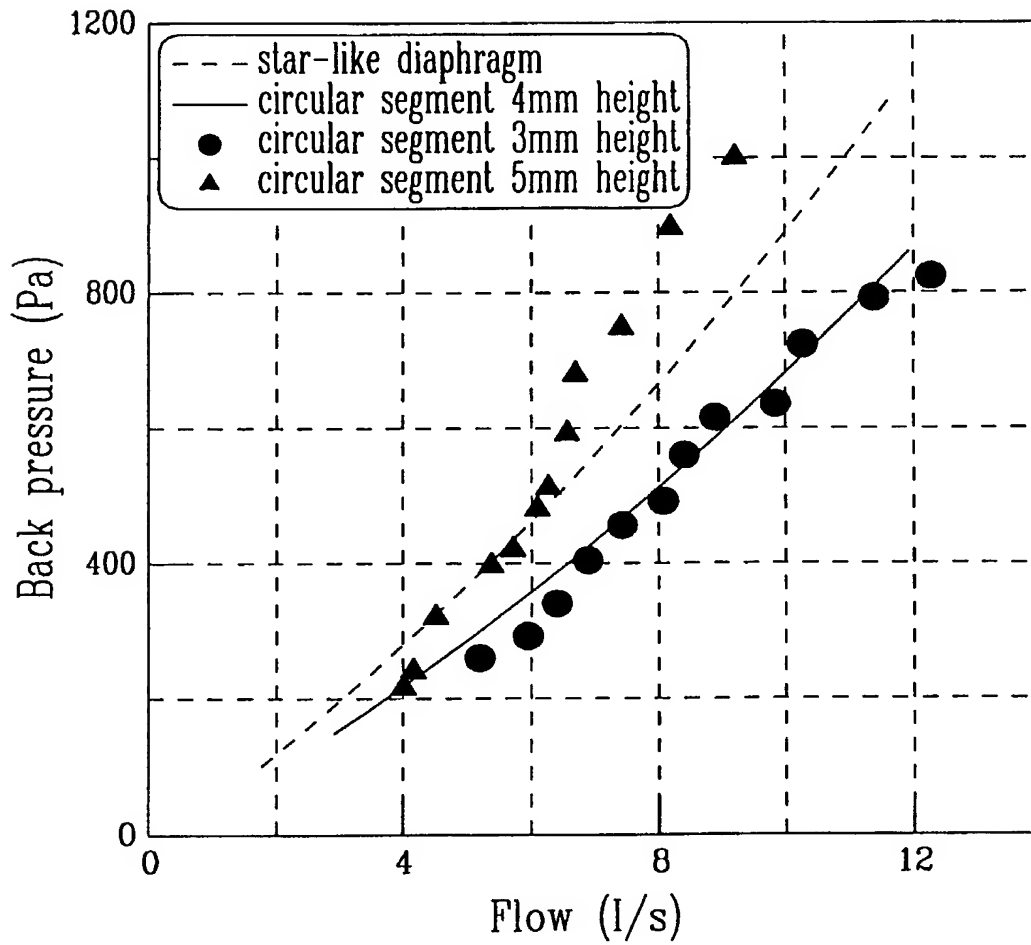


FIG. 4

4/16

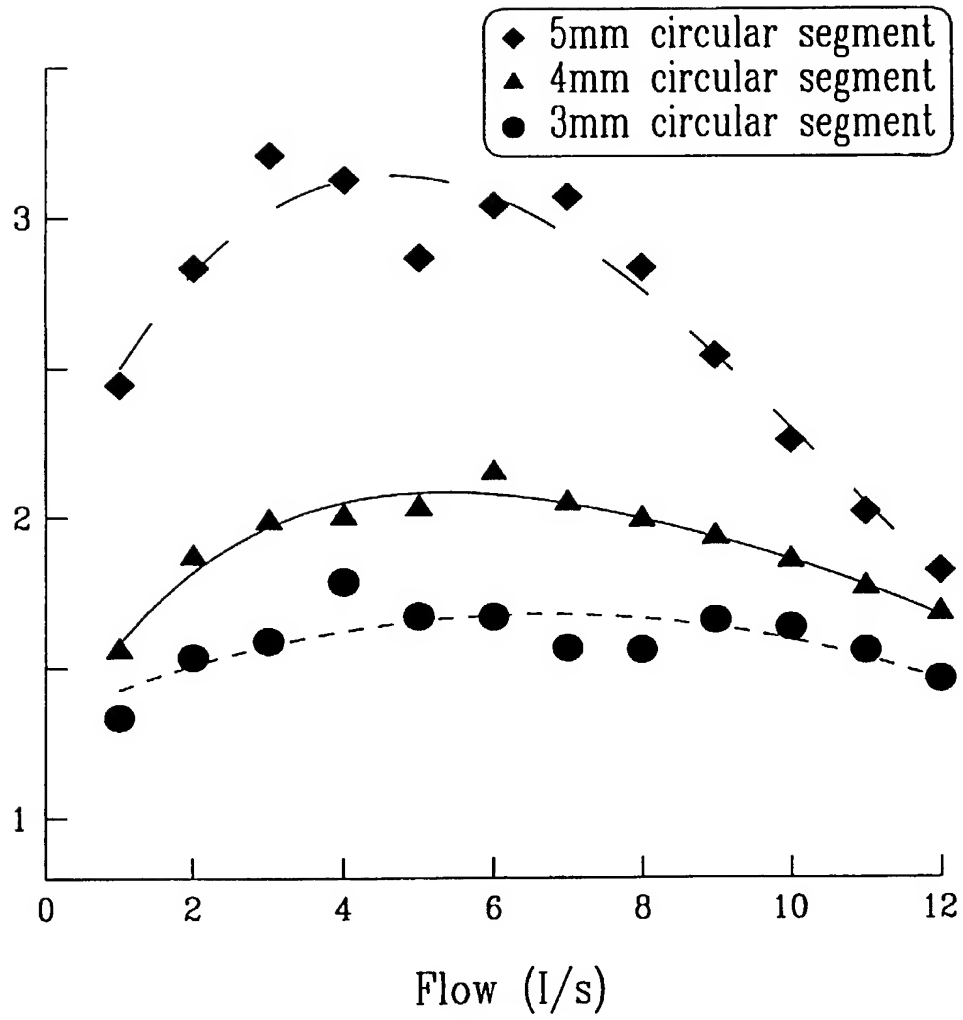


FIG. 5

5/16

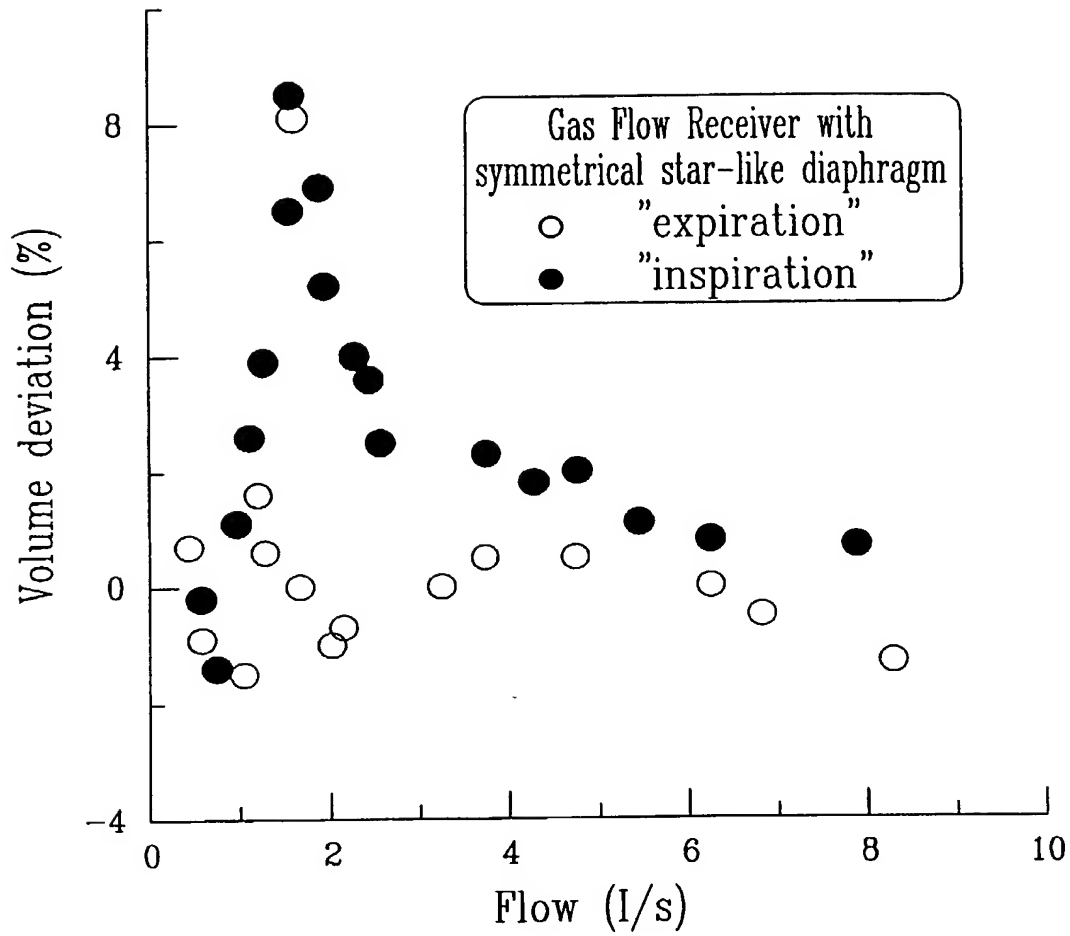


FIG. 5

6/16

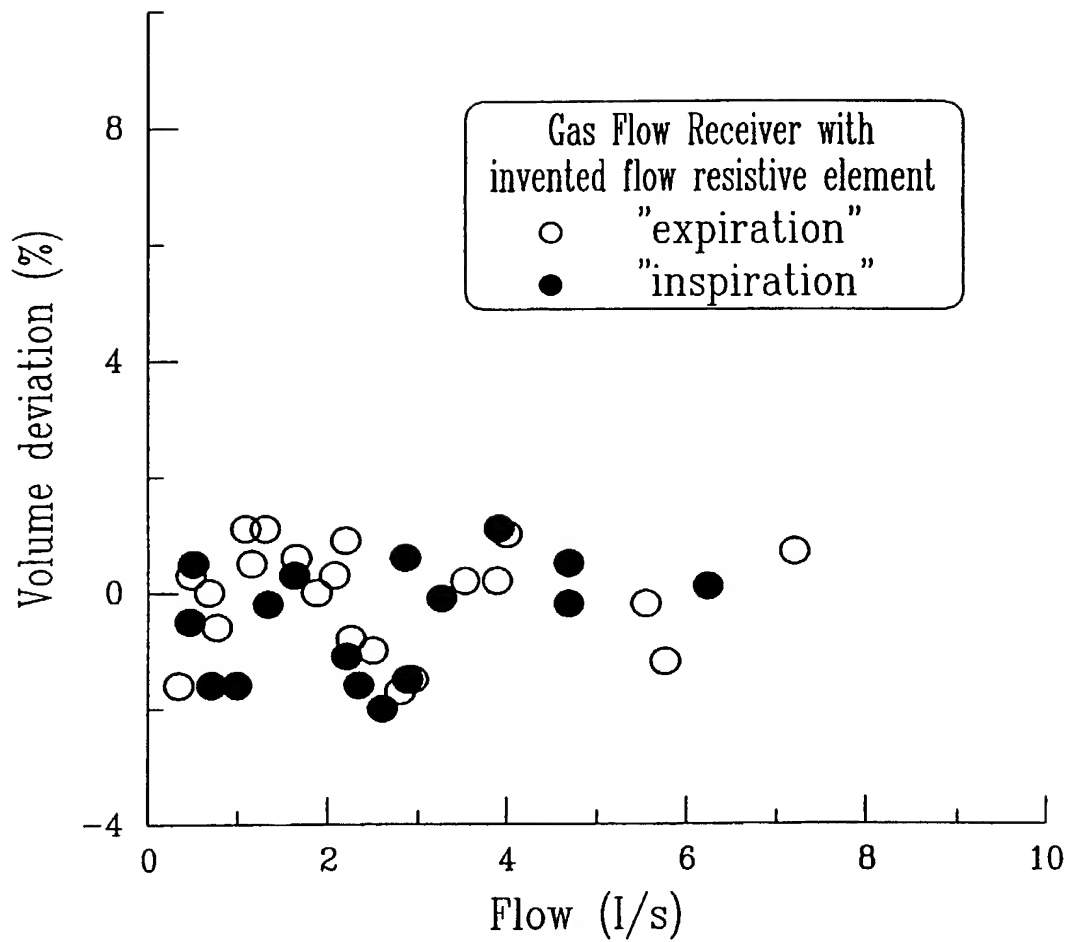
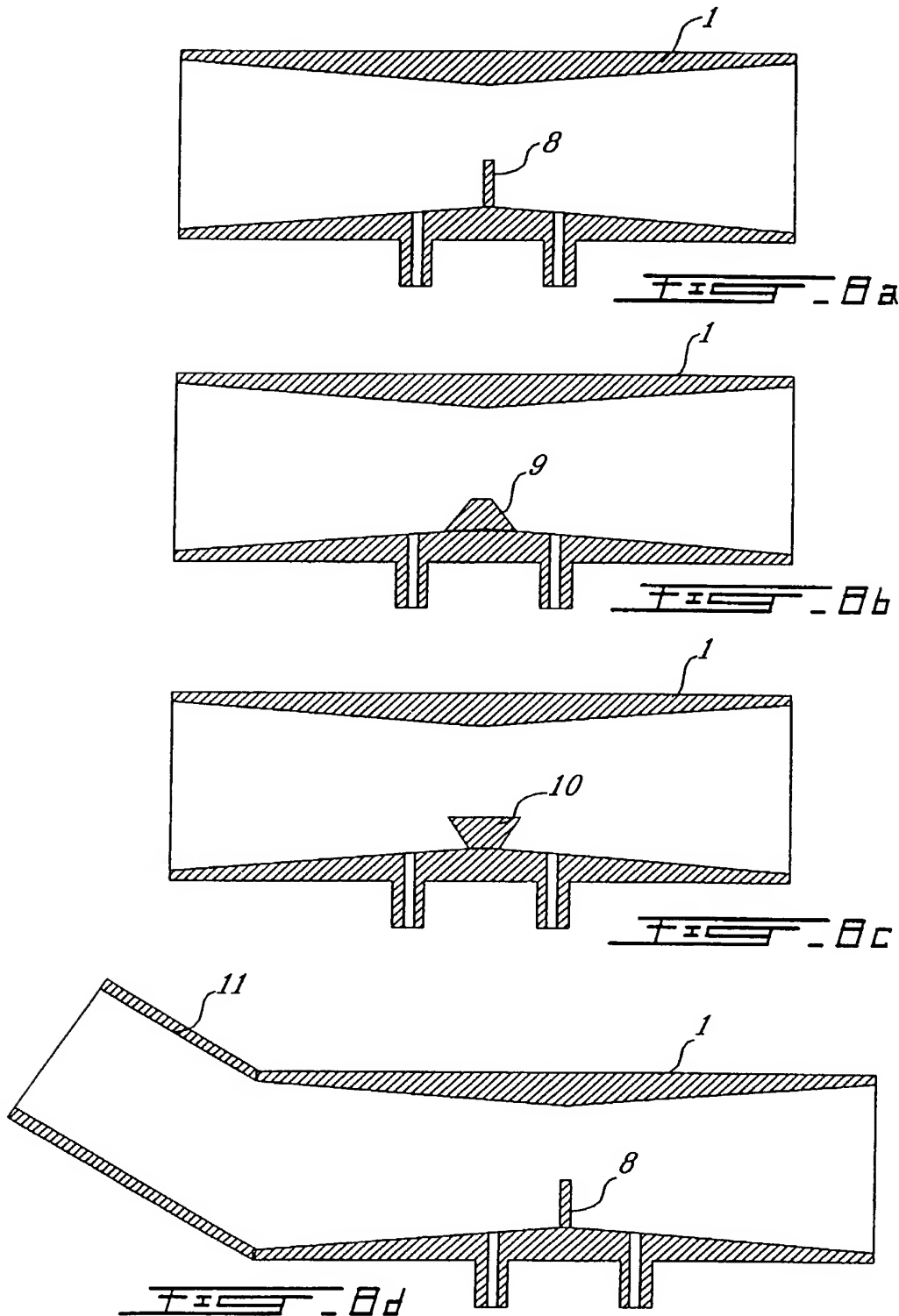


FIG. 7

7/16



8/16

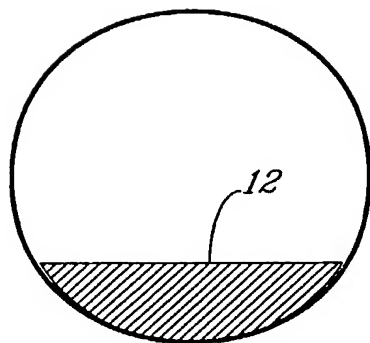


FIG. 9a

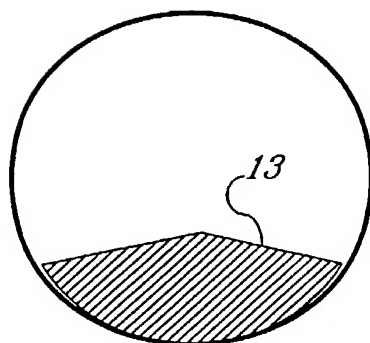


FIG. 9b

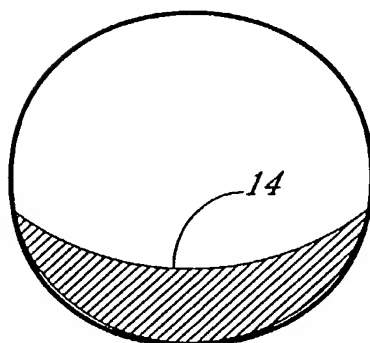
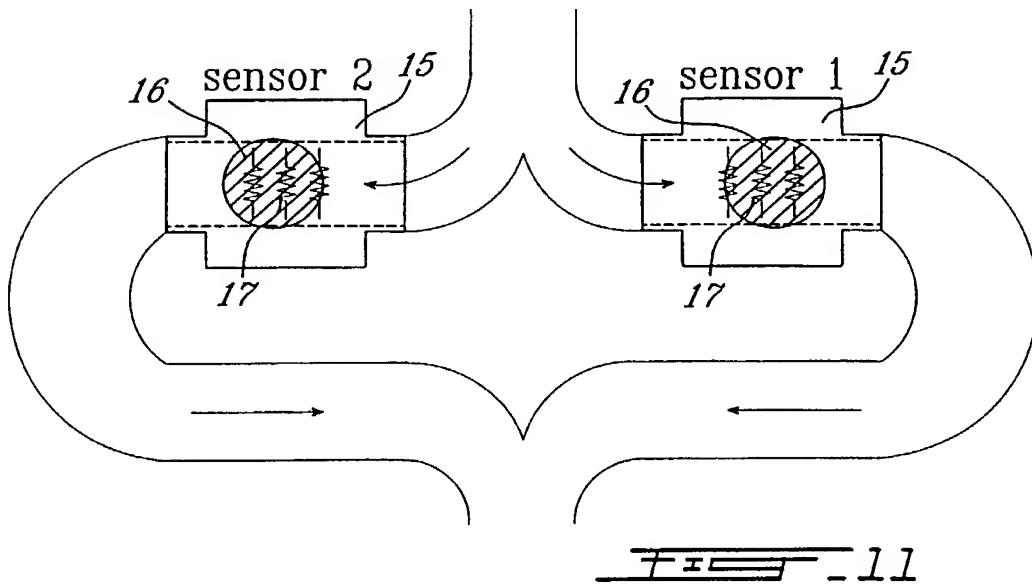
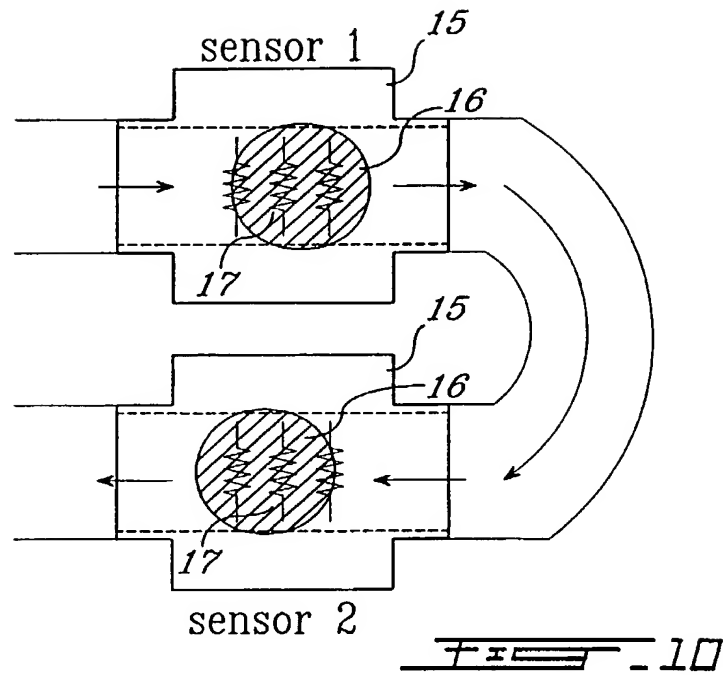


FIG. 9c

9/16



10/16

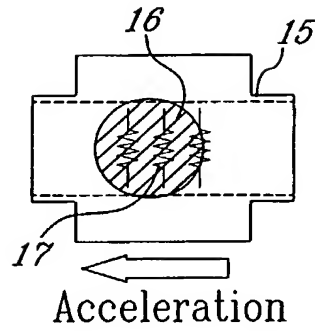


FIG. 12

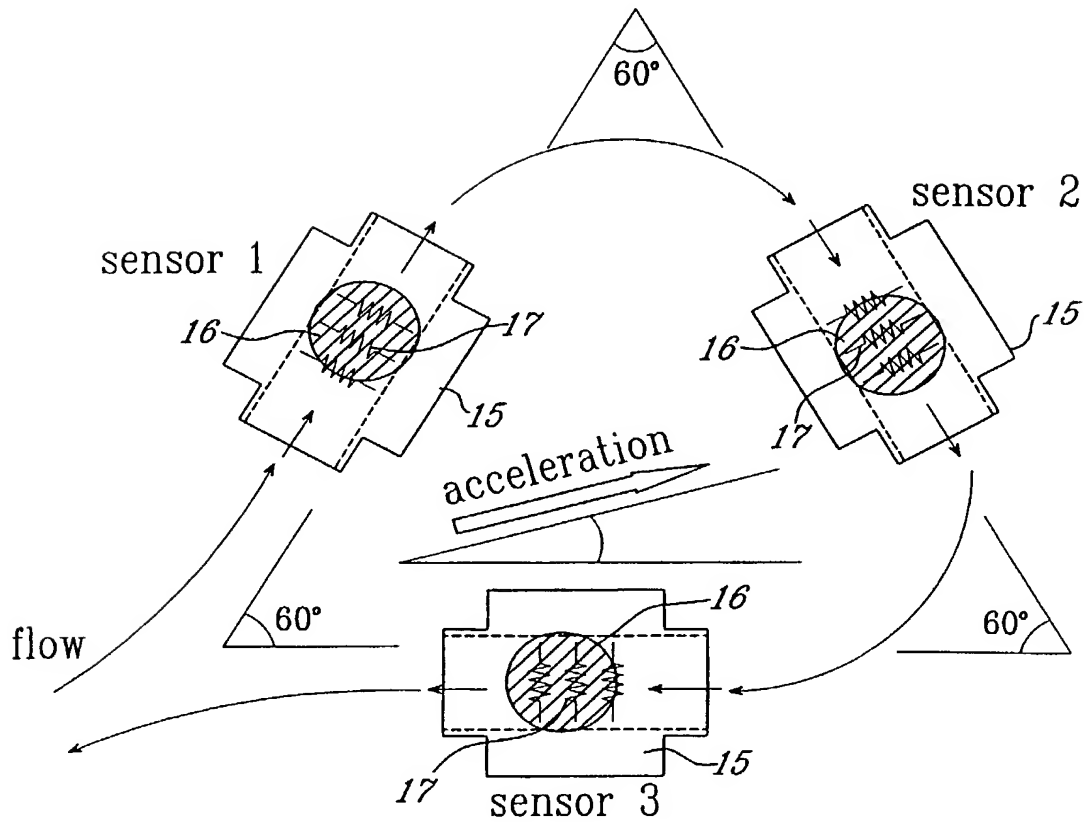
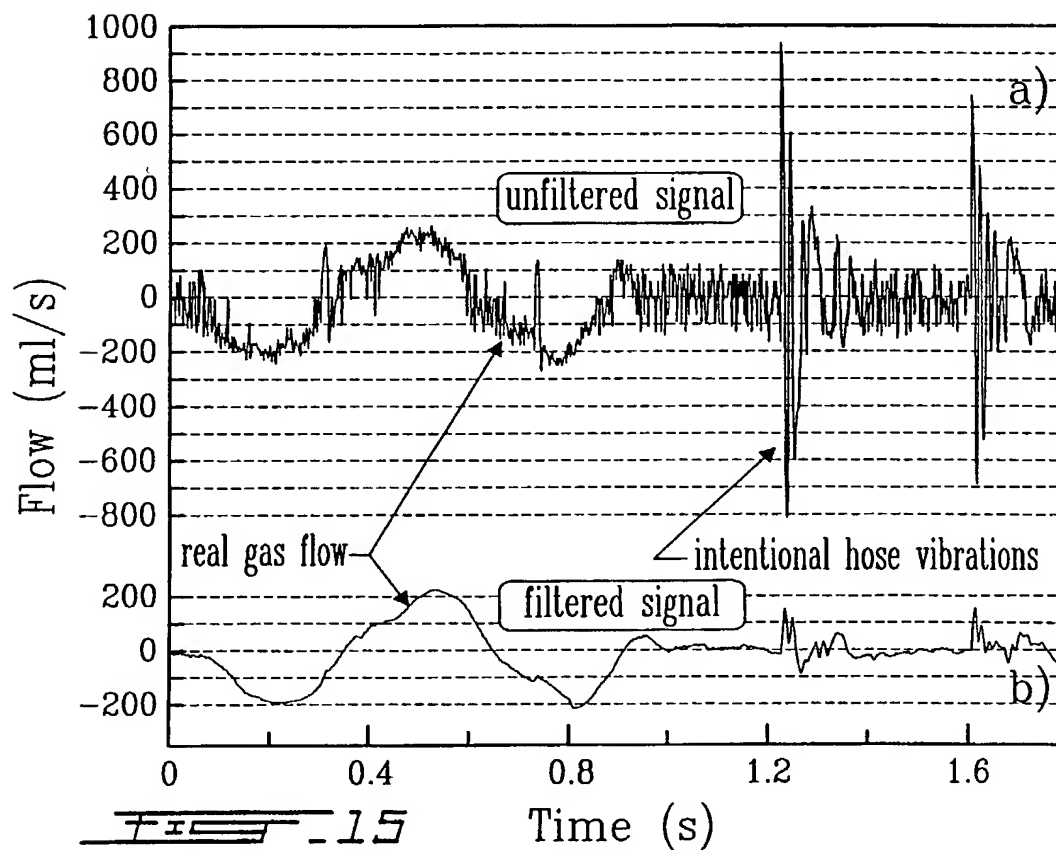
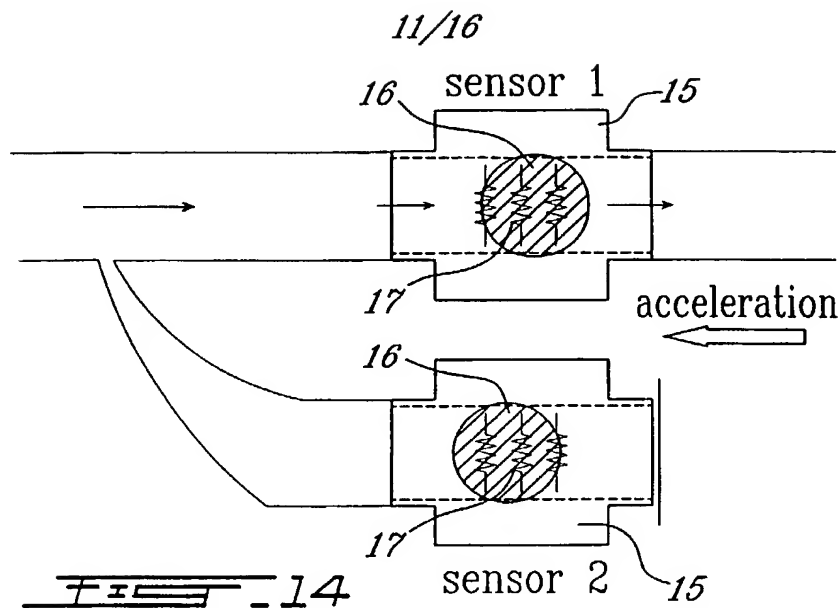
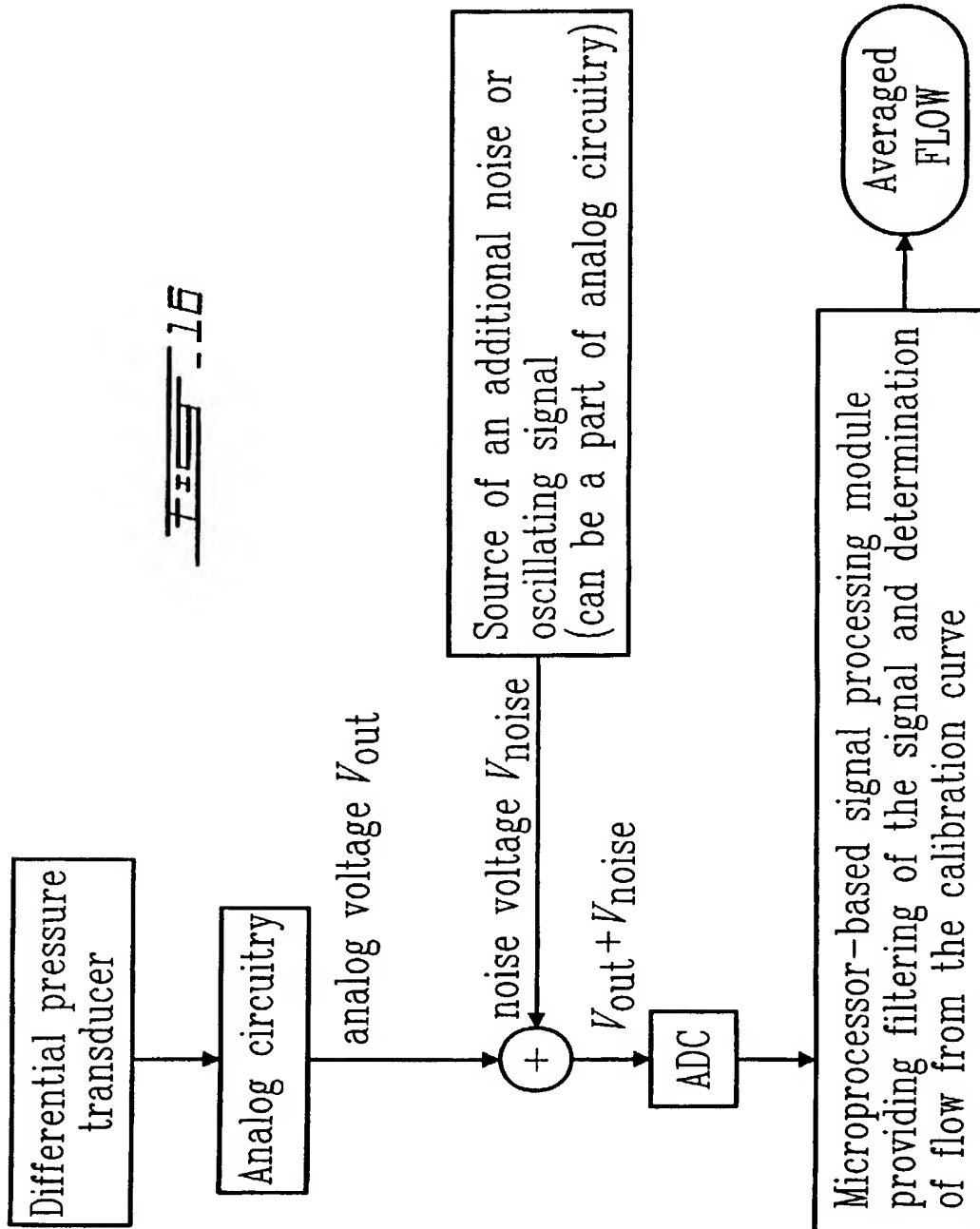


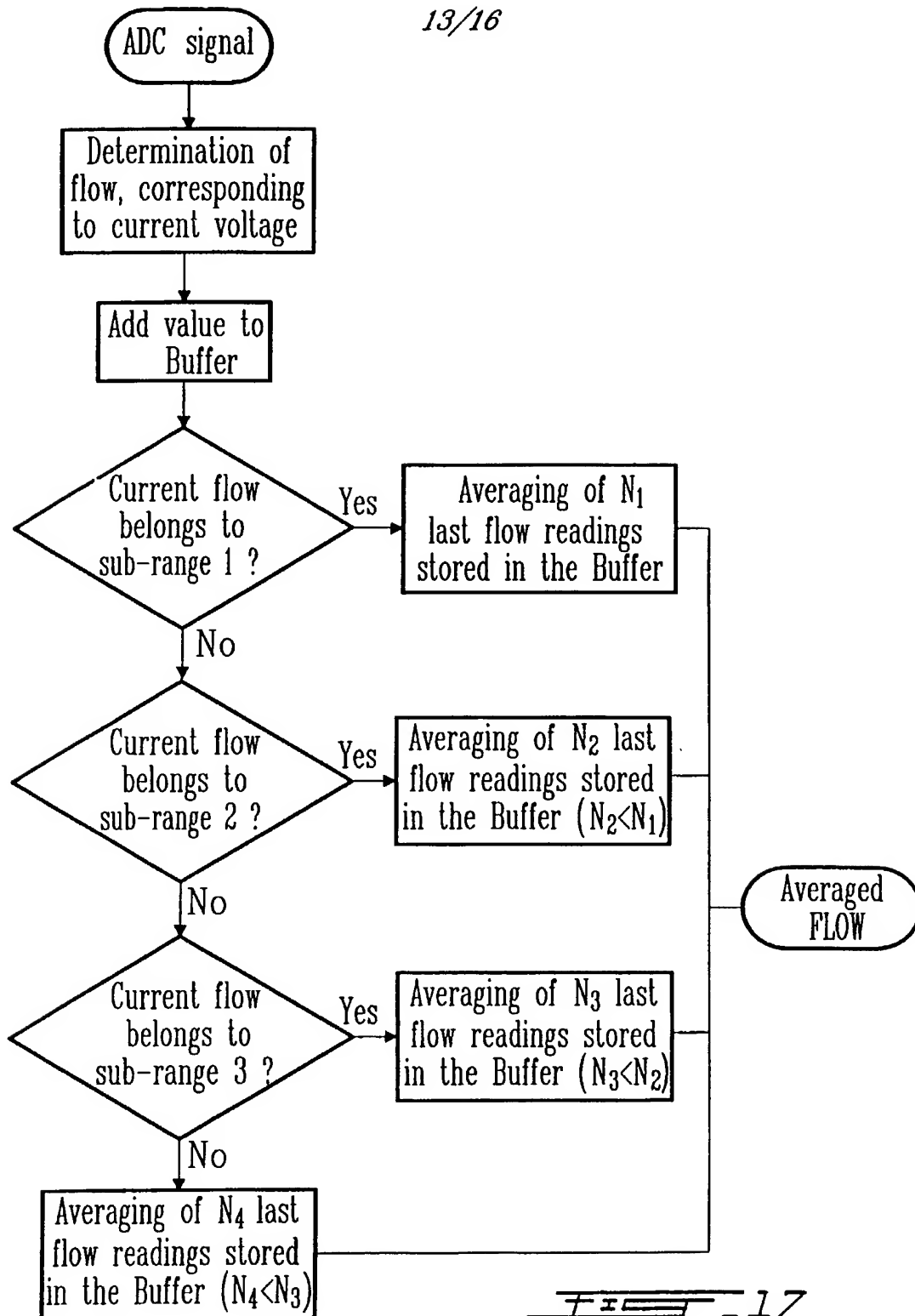
FIG. 13



12/16



13/16

FIG. 17

14/16

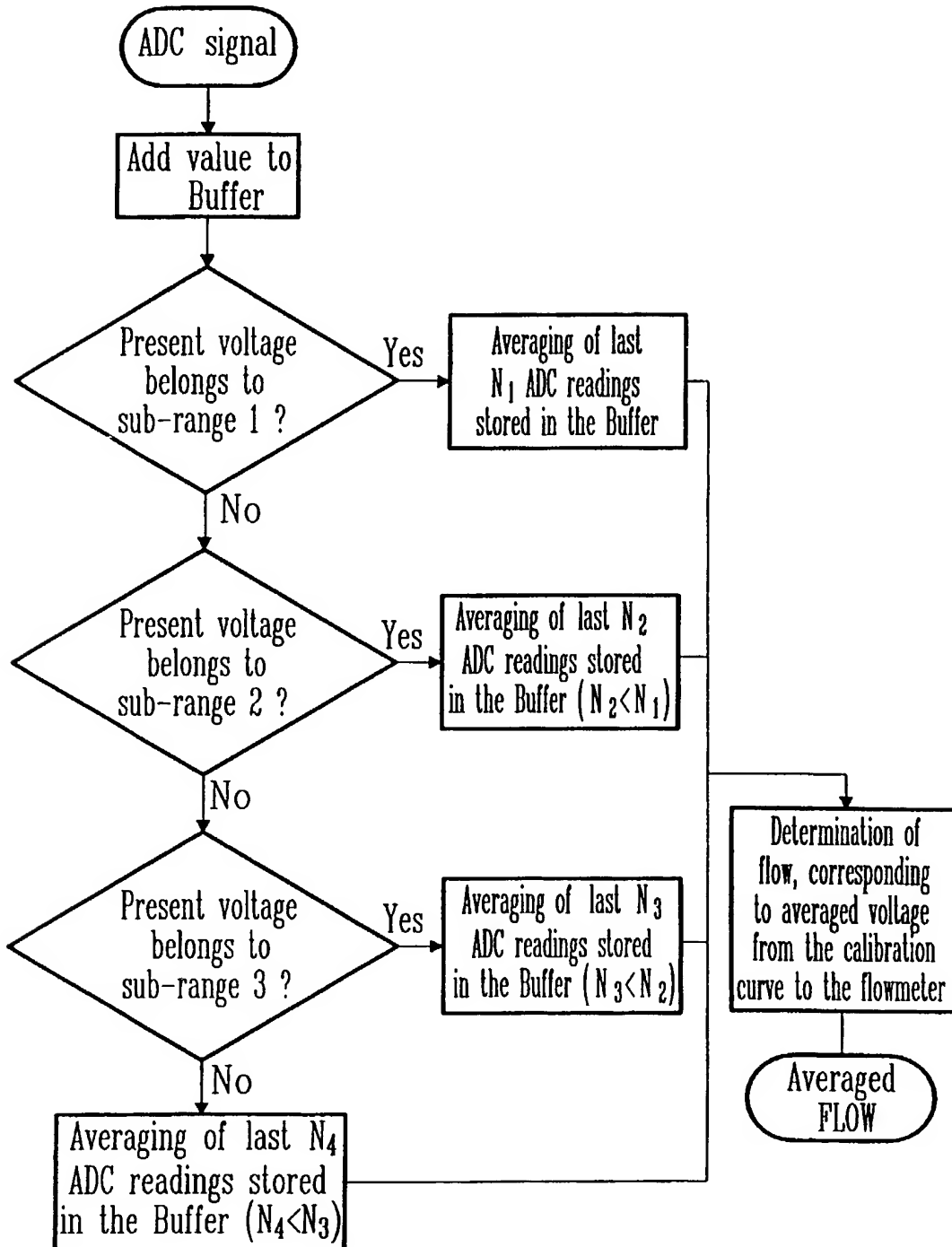


FIG. 10

15/16

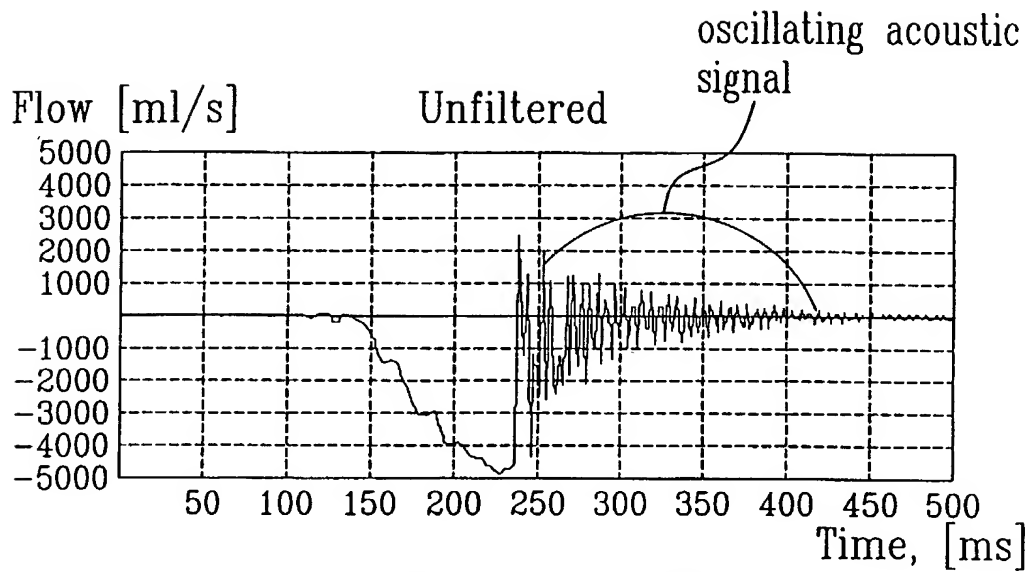


FIG. 19a

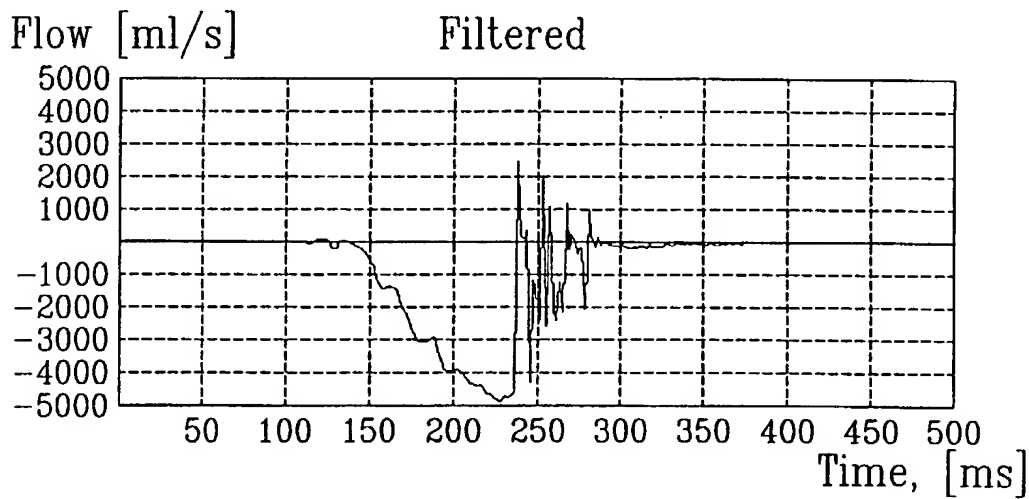
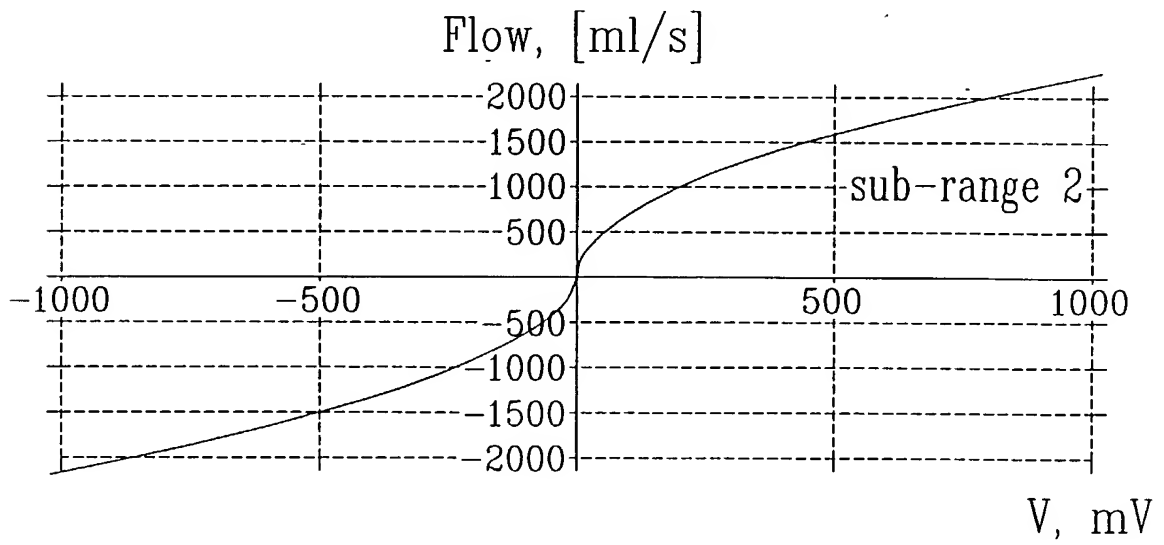
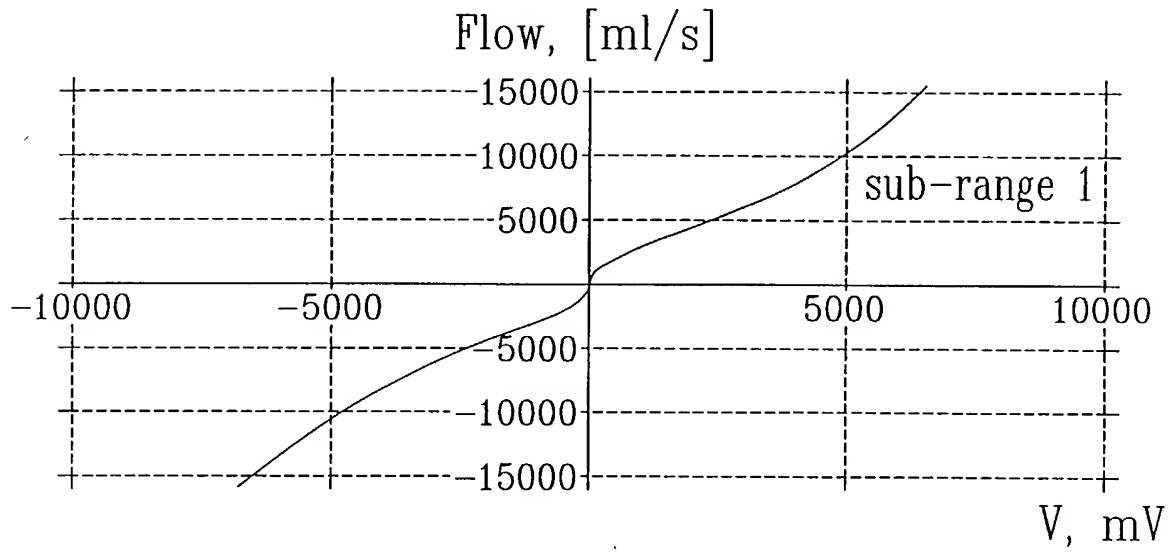


FIG. 19b

16/16



FIS - 20

Declaration and Power of Attorney for Patent Application

Déclaration et Pouvoir pour Demande de Brevet French Language Declaration

En tant qu'inventeur ci-après désigné, je déclare par la présente que:

Mon domicile, mon adresse postale et ma nationalité sont tels que figurant ci-dessous à côté de mon nom.

Je crois être le premier inventeur original et unique (si un seul nom est mentionné ci-dessous), ou l'un des premiers co-inventeurs originaux (si plusieurs noms sont mentionnés ci-dessous) de l'objet revendiqué, pour lequel une demande de brevet a été déposée concernant l'invention intitulée

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

"SEVERAL GAS FLOW MEASURING DEVICES AND SIGNAL PROCESSING METHODS"

et dont le mémoire descriptif est ci-joint à moins que la case suivante n'ait été cochée:

☐ a été déposée le _____ sous le numéro de demande des États-Unis ou le numéro de demande internationale PCT _____ et modifiée le _____ (le cas échéant).

Je déclare par la présente avoir révisé et compris le contenu du mémoire descriptif ci-dessus mentionné, incluant les revendications, telles que modifiées par toute modification ci-dessus mentionnée.

Je reconnais devoir divulguer toute information pertinente à la brevetabilité, tel que défini dans le Titre 37, §1.56 du Code fédéral des réglementations.

Je revendique par la présente la priorité étrangère, en vertu du Titre 35, §119(a)-(d) ou §365(b) du Code des États-Unis, sur toute demande étrangère de brevet ou certificat d'inventeur ou, en vertu du Titre 35, §365(a) du même Code, sur toute demande internationale PCT désignant au moins un pays autre que les États-Unis et figurant ci-dessous et, en cochant la case, j'ai aussi indiqué ci-dessous toute demande étrangère de brevet, tout certificat d'inventeur ou toute demande internationale PCT

the specification of which is attached hereto unless the following box is checked:

☒ was filed on September 1, 2000 as United States Application Number or PCT International Application Number PCT/CA00/01026 and was amended on _____ (if applicable).

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations., §1.56.

I hereby claim foreign priority under Title 35, United States Code, §119(a)-(d) or §365 (b) of any foreign application(s) for patent or inventor's certificate, or §365(a) of any PCT International application which designated at least one country other than the United States, listed below, and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or PCT International application having a filing date before that of the application

French Language Declaration

ayant une date de dépôt précédant celle de la demande à propos de laquelle une priorité est revendiquée.

on which priority is claimed.

Prior foreign application(s)
Demande(s) de brevet antérieure(s)

Priority Not Claimed
Droit de priorité non revendiqué

(Number)
(Numéro)

(Country)
(Pays)

(Day/Month/Year Filed)
(Jour/Mois/Année de dépôt)

☐

Je revendique par la présente tout bénéfice, en vertu du Titre 35, §119(e) du Code des États-Unis, de toute demande de brevet provisoire effectuée aux États-Unis et figurant ci-dessous.

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60/152,460
(Application No./ N° de demande)

September 3, 1999
(Filing Date/ Date de dépôt)

60/152,461
(Application No./ N° de demande)

September 3, 1999
(Filing Date/ Date de dépôt)

60/152,464
(Application No./ N° de demande)

September 3, 1999
(Filing Date/ Date de dépôt)

60/152,487
(Application No./ N° de demande)

September 3, 1999
(Filing Date/ Date de dépôt)

Je revendique par la présente tout bénéfice, en vertu du Titre 35, §120 du Code des États-Unis, de toute demande de brevet effectuée aux États-Unis, ou en vertu du Titre 35, §365(c) du même Code, de toute demande internationale PCT désignant les États-Unis et figurant ci-dessous et, dans la mesure où l'objet de chacune des revendications de cette demande de brevet n'est pas divulgué dans la demande antérieure américaine ou internationale PCT, en vertu des dispositions du premier paragraphe du Titre 35, §112 du Code des États-Unis, je reconnais devoir divulguer toute information pertinente à la brevetabilité, tel que défini dans le Titre 37, §1.56 du Code fédéral des réglementations, dont j'ai pu disposer entre la date de dépôt de la demande antérieure et la date de dépôt de la demande nationale ou internationale PCT de la présente demande:

I hereby claim the benefit under Title 35, United States Code, §120 of any United States application(s), or §365(c) of any PCT International application designating the United States, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of Title 35, United States Code, §112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, §1.56 which became available between the filing date of the prior application and the national or PCT International filing date of this application.

(Application No.)
(N° de demande)

(Filing Date)
(Date de dépôt)

(Status) (patented, pending, abandoned)
(Statut) (breveté, en cours d'examen, abandonné)

French Language Declaration

Je déclare que toute les déclarations faites dans la présente sont à ma connaissance, véridiques et que toutes les déclarations faites à partir de renseignements ou de suppositions sont tenues pour véridiques; et de plus, que toutes ces déclarations ont été faites en sachant que toute fausse déclaration volontaire ou son équivalent est passible d'une amende ou d'une peine d'emprisonnement, ou des deux, en vertu de la Section 1001 du Titre 18 du Code des États-Unis, et que de telles déclarations volontairement fausses risquent de compromettre la validité de la demande de brevet ou du brevet délivré à partir de celle-ci.

POUVOIR: En tant qu'inventeur désigné, Je nomme par la présente l'(les) avocat(s) et/ou agent(s) inclus sous le numéro de client officiel suivant, avec plein pouvoir de révocation et de substitution, chargés de poursuivre cette demande et de traiter toute affaire s'y rapportant avec l'Office des brevets et des marques: (mentionner le nom et le numéro d'enregistrement).

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

POWER OF ATTORNEY: As a named inventor, I hereby appoint the agents and/or attorneys included in the following Customer Number, with full power of substitution, association, and revocation, to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith: (list name and registration number)

Please send all correspondence and direct all telephone calls to: / Veuillez adresser toute correspondance et tout appel téléphonique à:



020988

PATENT AND TRADEMARK OFFICE

Full name of sole or first inventor (Nom complet de l'unique ou premier inventeur) Oleg GRUDIN	Citizenship (Nationalité) Ukraine	Date (dd/mm/yyyy) (jj/mm/aaaa) 28/02/2002
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Full name of second inventor (Nom complet du second co-inventeur) Alexander GENDIN	Citizenship (Nationalité) Ukraine	Date (dd/mm/yyyy) (jj/mm/aaaa) 28/02/2002
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Full name of third co-inventor (Nom complet du troisième co-inventeur) Gennadiy FROLOV	Citizenship (Nationalité) Ukraine	Date (dd/mm/yyyy) (jj/mm/aaaa) 28/02/2002
Residence and Post Office address (Domicile et adresse postale) Apt. 121, 3445 Cote-Des-Neiges, Montréal, Québec H3H 1T5, Canada	Third Inventor's signature (signature du troisième inventeur) 	
Full name of fourth co-inventor (Nom complet du quatrième co-inventeur)	Citizenship (Nationalité)	Date (dd/mm/yyyy) (jj/mm/aaaa)
Residence and Post Office address (Domicile et adresse postale)	Fourth Inventor's signature (Signature du quatrième inventeur)	